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Rotating Biological Contractors Hydraulic Versus Organic Loading

Columbus City Utilities, IN

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ROTATING BIOLOGICAL CONTACTORS HYDRAULIC VERSUS ORGANIC LOADING

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DISCLAIMER

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

The study evaluates the comparative performance of two plant-scale rotating biological contactor (RBC) treatment trains operating in parallel; one side operating on the basis of hydraulic loading and the other side operating on the basis of organic loading. Organic removal efficiencies and ammonia nitrogen conversions are measured. The treatment performance data and relationships developed provide information for making technical decisions about both the applicability and constraints of organic versus hydraulic loading and process configurations for RBC technology in municipal wastewater treatment.

Francis T. Mayo
Director
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ABSTRACT

Conventional and alternative flow configurations of rotating biological contactors were compared for soluble organic carbon and ammonia-nitrogen removal. Each treatment train contained eight shafts with a cumulative surface area of 800,000 ft^2. The hydraulic bay used the conventional flow configuration with eight single-shaft stages. The organic bay was modified so that the first stage contained four shafts, the second stage contained two shafts, and the third and fourth stages each contained one shaft. The flowrate was varied from 50% to 200% of design flow, with the two bays operating in parallel below 150% of design flow. After treatment by 400,000 ft^2 of surface area, the hydraulic bay had soluble cBOD concentrations that were lower than those in the organic bay in the parallel flow experiments. Above 400,000 ft^2 no statistically significant difference occurred in souble cBOD concentrations. Ammonia-nitrogen concentrations were lower in the hydraulic bay after 400,000 and 600,000 ft^2 of treatment area. There was no statistical difference in ammonia-nitrogen concentrations above 600,000 ft^2 of treatment.

This report was submitted in fulfillment of Cooperative Agreement No. CR-807463 by Indiana University, School of Public and Environmental Affairs, SIECO, Inc., and the City of Columbus, Indiana, under the sponsorship of the U.S. Environmental Protection Agency and the City of Columbus. This report covers the period August 1980 to October 1984, and work was completed as of October 1984.

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ENGLISH TO METRIC CONVERSIONS

English Units	X Conversion	Metric Units
mil (=.001 inch)	0.025	mm
ft	0.305	m
ft^2	0.093	m^2
ft^3	0.028	m^3
gal	3.79	L
gpm	6.31×10^{-5}	m^3/s
mgd	3800	m^3/d
gpd/ft^2	4.07×10^{-2}	$m^3/m^2 \cdot d$
lb	0.45	kg
lbs/day/1000 ft^2	4.88×10^{-3}	$kg/m^2 \cdot d$

DEFINITIONS AND ABBREVIATIONS

$cBOD_5$:	Carbonaceous BOD; that BOD which is determined using a standard cBOD analysis with the addition of an inhibitor (2-chloro-6-trichloro methyl-pyridine; Hach 2533) to prevent the oxidation of ammonia which would show up as an oxygen depletion and thus be calculated as part of the BOD.
Total $cBOD_5$:	A nitrification inhibited BOD test run on an unfiltered sample.
$ScBOD_5$:	A nitrification inhibited soluble BOD test run on a sample filtered through a glass fiber filter (Whatman 934 AH) to remove the filterable residue (suspended solids).
SS:	Suspended solids = total filterable residue.
TKN:	Total Kjeldahl nitrogen is the sum of the ammonia nitrogen plus organic nitrogen.

SECTION 1

INTRODUCTION

The wastewater treatment plant at Columbus, Indiana is a 12.4 million gallon-per-day (mgd) facility utilizing rotating biological contactors (RBC) for secondary treatment and nitrification. Expansion and improvements to the plant occurred in 1976 with the selection of the RBC process to provide removal of carbonaceous biochemical oxygen demand (cBOD) and conversion of ammonia nitrogen to other nitrogen forms. The RBC portion of the plant consists of ten treatment bays with eight shafts each. Because the size of the Columbus installation allowed the plant to operate at near design conditions while using only a portion of the facility, a number of the RBC units were available for experimentation. A flow diagram for the entire treatment plant is shown in Figure 1. Wastewater that has undergone conventional primary treatment enters the RBC train for secondary treatment. The treated wastewater is then passed on to a clarifier and a chlorination tank before being discharged to the East Fork of White River. Detailed plant design data are presented in Appendix A.

The overall objective of this study was to provide plant-scale experimental data in order to develop appropriate design and operational criteria for RBC wastewater treatment facilities. The specific goal of this study was to determine RBC effectiveness over varying flow rates and organic loads for two different flow schemes operating side-by-side. The first flow scheme was operated on the basis of hydraulic loading rates, with stages of equal media surface area. The second flow scheme operated on the basis of organic loading rates, with each stage receiving approximately equal mass loading of organic matter (cBOD). Hydraulic and organic loading rates were varied from 50% to 200% of design flow to determine treatment effectiveness and limitations for the two operational schemes.

Figure 2 depicts the flow schemes for the hydraulic bay and the organic bay. A portion of the primary treated wastewater was diverted to the two experimental bays. The hydraulic bay consisted of eight shafts in conventional series configuration. In this bay, stages and shafts were synonymous. The organic bay consisted of eight shafts in a tapered configuration. The primary treated wastewater was evenly divided among four parallel shafts in stage one, followed by two shafts in stage two, and one shaft each in stages three and four. A side stream of the effluent from each bay was diverted to a pilot clarifier to characterize settled effluent quality.

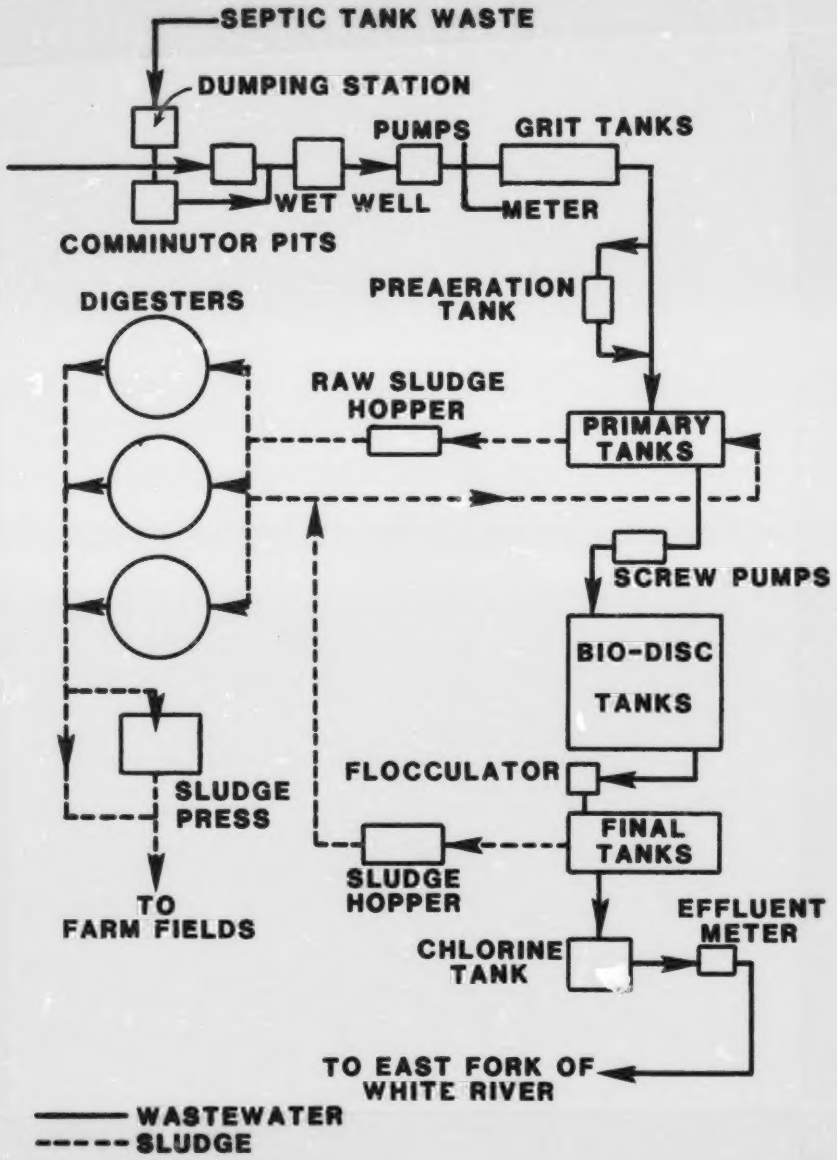

SEPTIC TANK WASTE
DUMPING STATION
PUMPS
GRIT TANKS
WET WELL
METER
COMMINUTOR PITS
PREAERATION TANK
DIGESTERS
RAW SLUDGE HOPPER
PRIMARY TANKS
SCREW PUMPS
BIO-DISC TANKS
FLOCCULATOR
SLUDGE PRESS
FINAL TANKS
SLUDGE HOPPER
TO FARM FIELDS
EFFLUENT METER
CHLORINE TANK
TO EAST FORK OF WHITE RIVER
WASTEWATER
SLUDGE

Figure 1. Flow diagram of City of Columbus wastewater treatment plant.

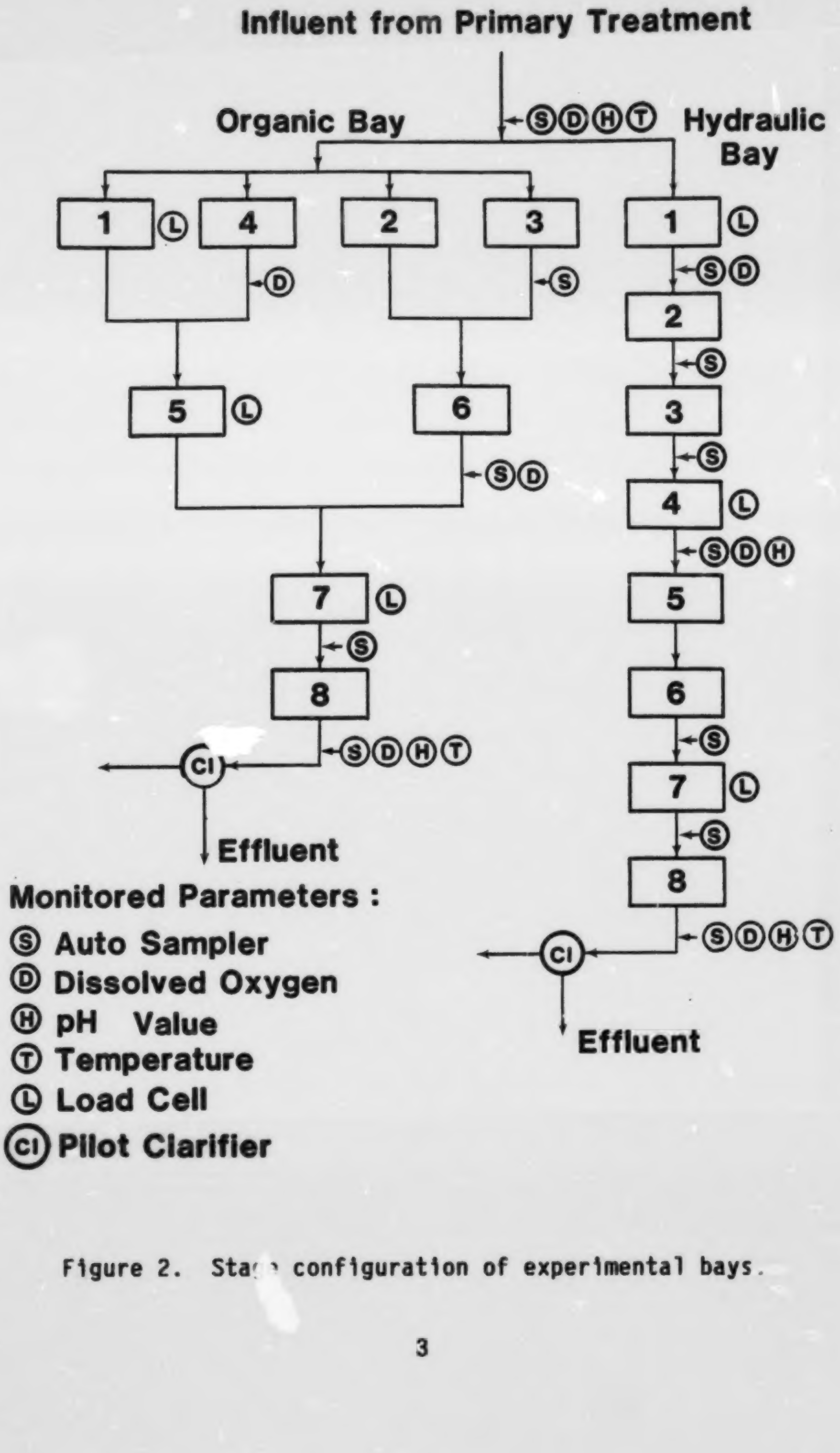

Influent from Primary Treatment
Organic Bay
Hydraulic Bay
S D H T
1 L
4
2
3
D
S
5 L
6
S D
7 L
S
8
S D H T
Cl
Effluent
1 L
S D
2
S
3
S
4 L
S D H
5
6
S
7 L
S
8
S D H T
Cl
Effluent
Monitored Parameters :
S Auto Sampler
D Dissolved Oxygen
H pH Value
T Temperature
L Load Cell
Cl Pilot Clarifier

Figure 2. Stage configuration of experimental bays.

SECTION 2

CONCLUSIONS

The following specific conclusions are drawn from the research completed at the Columbus RBC wastewater treatment plant:

1. The mean total cBOD concentration in the influent for the various experiments ranged from 63 to 95 mg/L and from 72 to 95 mg/L for the hydraulic and organic bays, respectively. Total cBOD removal efficiency in the hydraulic bay was stable at 83% for all the design flow experiments, with exceptions noted at 150% and 200% of design flow. In the organic bay, the removal efficiency measured 79% to 85% as the flow changed from 50% to 75% design flow, and it remained steady at the 85% level through the 125% design flow studies. When the flow was further increased, the treatment efficiency deteriorated to 72% at 200% design flow in the organic bay and to a level of 67% as the flow changed from 175% to 200% design flow in the hydraulic bay. These treatment efficiency reductions were probably due to the reduced residence times in the treatment bays.

2. The 4-2-1-1 staging configuration of the organic bay allowed greater cBOD loading to this treatment train without exceeding the EPA recommended maximum organic loading rate (2.5 lb cBOD/day per 1,000 ft^2) during the first stage of treatment. First-stage, soluble cBOD loadings to the organic bay ranged from a low of 0.44 lb cBOD/day per 1,000 ft^2 in the 50% design flowrate experiment to a high of 2.2 lb cBOD/day per 1,000 ft^2 in the 200% design flowrate experiment. For comparison, the first-stage soluble cBOD loadings in the hydraulic bay ranged from a low of 1.8 lb cBOD/day per 1,000 ft^2 in the 50% design flowrate experiment to a high of 7.3 lb cBOD/day per 1,000 ft^2 in the 150% design flowrate experiment. Furthermore, the first-stage cBOD loading in the hydraulic bay exceeded EPA's guideline in all experiments where the flowrate equalled or exceeded 75% of the design flowrate. The ability to achieve low effluent cBOD concentrations and comply with the EPA organic loading guideline is a major advantage of the organic bay's staging configuration compared with the more commonly used flow scheme in the hydraulic bay.

3. The experimental means for soluble cBOD concentration in the influent to the experimental RBC treatment trains ranged from 29 to 47 mg/L and 26 to 46 mg/L for the hydraulic and organic bays, respectively. Both treatment trains were capable of consistently reducing the influent cBOD to less than 10 mg/L under flowrate variations between 50% and 200% of the design flowrate. Mean effluent soluble cBOD levels as low as 2 to 4 mg/L were achieved in both treatment configurations at flowrates less than 100% of the design flowrate. Effluent levels of soluble cBOD were increased

slightly as the experimental flowrate exceeded 75% of the design flowrate. The highest mean effluent soluble cBOD level for the organic bay was 8.3 mg/L at 200% of design flowrate (Experiment 12). Similarily, the highest effluent soluble cBOD concentration in the hydraulic bay was 9.2 mg/L, again at the 200% design condition (Experiment 9). The percent removal of mean soluble cBOD exceeded 80% for all experiments, except for the hydraulic bay 200% of design flowrate experiment where a 73% removal was recorded. Soluble cBOD removals between 87% and 94% were evident for both the hydraulic and organic bays at flowrates at or below 100% of the design flowrate.

4. The removal of soluble COD followed a pattern similar to that found for soluble cBOD. Mean soluble COD concentrations in the effluent from the hydraulic and organic bays were always below 60 mg/L. Effluent COD levels of 30 to 40 mg/L were achieved in both treatment trains at flowrates equal to or less than 100% of the design flowrate, except for hydraulic bay Experiment 3 (75% design flow), which had an uncommonly high mean effluent COD value of 52 mg/L. Cumulative percent removal of COD ranged from 49% to 74% and 59% to 72% in the hydraulic and organic bays, respectively. The percentage of COD removed increased as the experimental flowrate was decreased.

5. The hydraulic treatment bay achieved slightly lower soluble cBOD concentrations after 400,000 ft^2 surface area of treatment compared with the organic bay. This observation was based on the comparison of daily, soluble cBOD concentrations for those experiments during wich the hydraulic bay and organic bay were compared on a true side-by-side basis. The superior performance of the hydraulic bay at 400,000 ft^2 of treatment was confirmed from statistical analysis with a 90% confidence level. Again in parallel flow experimental comparisons, the concentrations of (daily) soluble cBOD in the hydraulic and organic bays were not statistically different after treatment by 600,000 ft^2 (or more) of media surface area.

6. In both the organic and hydraulic treatment bays, the concentration of soluble cBOD and COD at each stage of treatment was related to the cumulative fluid retention time. A majority of the observed removal occurred within the first hour of treatment, and the rate of removal of both cBOD and COD decreased with increased retention time. For practical purposes, the ultimate removal achieved was nearly complete after only two hours of treatment (fluid retention time). This observation confirms that (regardless of the flow configuration) RBC treatment technology is a "high-rate" process capable of achieving low effluent cBOD and COD concentrations with only a short wastewater retention time. For example, the relationship of soluble cBOD remaining versus wastewater retention time, which was developed from the hydraulic bay experiments, predicts an effluent soluble cBOD concentration of 10 mg/L after one hour of treatment and a level of 5 mg/L after only two hours of treatment.

7. The organic bay flow configuration offers several advantages in operational performance compared with the commonly used hydraulic bay configuration. The equalization of organic loading between stages that is accomplished in the organic bay flow configuration allows this treatment

system to (a) meet EPA's organic loading guideline; (b) better withstand organic shock loadings; (c) control the growth of nuisance organisms, odors and similar concerns; (d) maintain acceptable dissolved oxygen values in all stages of treatment, thereby maintaining an aerobic treatment process and eliminating oxygen transfer as a rate limiting step in the removal of organic matter; and (e) control the occurrence of excess biomass growth that can cause structural failure of the RBC's shaft. These operational advantages are achieved in the organic bay flow configuration with no adverse impact on treatment performance. As noted previously (see Conclusion 5), a slight reduction in the cBOD removal occurred in the organic bay at 400,000 ft^2 of media area compared with the hydraulic bay. This difference was small, however, and was not recorded after 600,000 ft^2 of surface area was treated.

8. The level of ammonia-nitrogen present in the effluent from the hydraulic and organic bays varied depending on the flowrate (and organic loading) treated. In experiments below 100% design flowrate, both treatment bays were able to reduce the influent ammonia-nitrogen level below 1.0 mg/L, indicating that effective nitrification was occurring. For the 100% to 150% design flowrate experiments, some reduction in the concentration of ammonia-nitrogen was evident, although only partial nitrification of the effluent was accomplished. Very little to no change in the ammonia-nitrogen concentration was evident between stages in either the organic or hydraulic treatment bays at the 175% and 200% design flowrate experiments. This shows that nitrification was not significant at these high flow conditions.

9. In the parallel flow experiments in which the hydraulic and organic bays were compared directly, the ammonia-nitrogen concentrations after 400,000 ft^2 and 600,000 ft^2 of treatment were lower in the hydraulic bay. Statistical analysis supports this conclusion with a 95% confidence level. The superior performance of the hydrualic bay is thought to have resulted from the increased level of staging in this treatment bay's flow scheme (compared with the organic bay's lower degree of staging). Increased treatment performance is expected with increased staging for processes in which the kinetic order is something other than zero order.

10. Nitrite-nitrate-nitrogen production was closely associated with the removal of ammonia-nitrogen. As the flowrate was increased, the concentration of nitrite-nitrate-nitrogen produced decreased and it occurred in later stages of treatment. At flowrates exceeding 150% of the design flowrate, little to no nitrite-nitrate-nitrogen production was evident in either the organic or hydraulic bays. This occurrence confirms that nitrification was not occurring at the 175% or 200% flow conditions.

11. The organic bay showed the ability to resume nitrification shortly after a reduction from 200% to 75% of the design flowrate. This result suggests that nitrifying organisms were present in the 200% flowrate experiment, but that they were ineffectve in lowering the ammonia concentration. Conversely, increasing the flowrate from 50% to 200% of design flowrate resulted in an immediate and significant decrease in the removal of ammonia that was occurring in the 50% design flowrate experiment.

SECTION 3

RECOMMENDATIONS

1. Parallel experiments in the hydraulic bay and the organic bay at 150%, 175%, and 200% of design flow are needed to compare these two configurations at high flowrates. These would be useful in determining the flowrates at which the hydraulic bay performs better, the bays perform equally, or the organic bay performs better.

2. Continued study of the nitrification process in RBC's is needed. Especially important considerations are the relationship of nitrification to dissolved oxygen concentrations, organic loading, and staging configuration.

3. A quantitative study of "nuisance" organisms such as Beggiatoa could provide information about conditions favoring their occurence and subsequent effects on efficiencies of organic removal and nitrification.

4. The study of other flow configurations might provide useful design information for plant optimization based on hydraulic loading, organic loading, and effluent requirements. In addition to the straight flow through and 4:2:1:1 configurations, a 3:2:1:1:1 configuration or other flow schemes may provide a maximum removal efficiency while minimizing organic loading to the first stage.

5. The relationships between shaft rotational speed and removal efficiency, power requirements, and biomass should be investigated. Again this could provide useful design and operator information with an emphasis on maximizing removal and minimizing power requirements.

SECTION 4

MATERIALS AND METHODS

BACKGROUND

The Columbus RBC Research Project consisted of two full scale trains of eight shafts with each shaft containing 100,000 ft^2 of media. One train was arranged for hydraulic loading and one for organic loading. Monitoring requirements included: Flow (continuous), dissolved oxygen (continuous and spot check), pH (continuous and spot check), temperature, (continuous and spot check) biochemical oxygen demand, chemical oxygen demand, total filterable residue, ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, biomass, and power (see Figure 2).

A typical experiment would last from 14 to 21 days with all parameters being monitored throughout the duration of the experiment. A total of 17 experiments were performed over a 2-year period. Careful coordination of six technicians in two laboratories was needed to ensure that the maximum amount of information was obtained and that the data collected were representative of the process being monitored.

QUALITY CONTROL

As with any experiment, the information which is used to draw conclusions must be as accurate and representative as possible. In order to provide this type of information and also as a requirement of the contract between the U.S. EPA, a Quality Control (QC)/Quality Assurance (QA) program was developed, reviewed, and accepted, (1). The program procedures include: duplicate analysis, the use of spiked samples with expected recoveries, expected deviations of standards (QC charts), goals for number of analyses completed and statistical analysis of standards. No extraordinary procedures were developed.

A rotating analysis schedule was developed between the two laboratories (City of Columbus and SIECO). This rotating schedule allowed each laboratory some flexibility in the number of samples tested each day and helped to serve as a self check on the analysis performed. Since the analytical results tended to follow a trend as the wastewater traveled through each experimental bay, it was relatively easy to spot anamolous results and investigate their causes. The procedure was found to be useful on several occasions and little effort was required to return the analysis to acceptable standards.

All data generated were reviewed by the individual analyst, compiled at each laboratory and transferred to specific test data sheets. These data were then reviewed by the Q.A. Program Manager before further data reduction.

Both laboratories participated in performance audits sponsored by the U.S. EPA with satisfactory results.

PROCESS MONITORING

During each experiment several parameters were monitored and recorded on a continuous basis, these were dissolved oxygen, pH and temperature. Dissolved oxygen monitoring created some problems because of the biomass which grew continuously on anything which was placed in the wastewater stream. The Rexnord Model 3000-5 Dissolved Oxygen meters were cleaned and calibrated daily. After a period of 12 to 16 hours, a noticeable downward drift was indicated on the strip chart recorders. It is believed that this was due to the biomass assimilating some of the DO before it could permeate the membrane for measurement. Spot checks with YSI Model 54 DO meters, calibrated to Winkler titrations (5), and actual Winkler titrations of the wastewater indicated that the measurements were accurate to ± 1 mg/L.

Temperature measurements were continously recorded using Rexnord Model 3100-5 temperature meters and Monitek strip chart recorders. Daily spot checks were made using the temperature probe of the YSI Mode 54 portable DO meters. pH measurements were similarly monitored using Rexnord Model 3750 pH monitors and the strip chart recorders. Daily spot checks were made.

Flows were spot checked using a totalizer and a stop watch. The flows had to agree to the flow cam indication to within ± 5%. Flows to the organic bay were balanced using standard orifice plates and a differential pressure meter. The differential pressure meter was checked for calibration semiannually by use of a water column manometer.

Composite sampling was accomplished by use of Isco Model 1580 and 1680 automatic samplers and the Foxboro magnetic flow meters. A signal from the flow integrator was fed to the Isco interface unit which issued a pulse signal every 10,000 gallons. These pulses could then be multiplexed by the samplers so that sampling frequency could be varied over a range of 10,000 to 100,000 gallons to accommodate the variation in the experimental flow rates and the amount of sample needed.

Samplers were kept cool with freeze packs in all but the extremes in temperature. During the very hot summer of 1983, ice was used to supplement their cooling capacity and heating tapes were used during the winter months to prevent freezing. Well mixed samples from each sampling location were split each morning and delivered to the respective laboratories so that analysis could begin immediately.

LOAD CELL MEASUREMENTS

Load cells were used to measure biomass weight, and in turn estimate the thickness of the biomass. This was accomplished by the use of a specially constructed hydraulic cylinder which was incorporated into the idle end bearing holder of the RBC shaft. The bearing holder was loosened, and a hydraulic pump used to raise the shaft slightly.

The amount of pressure needed to raise the shaft was thus proportional to the mass. By taking corrections for buoyancy due to submergence, an estimate of the total biomass was obtained. In practice, a calibration chart was provided by the manufacturer so that only pressure, shaft wall thickness and submergence were needed to obtain the necessary data.

POWER MEASUREMENTS

The measurement of three-phase power provided the most difficulty of any of the parameters during the course of the experiment. Our first attempts met with less than success, as we had no alternative means of cross checking the measurements obtained. Our basic assumption, that power was related to the voltage times the amperage times 1.73 (for three phase power), neglected to take into account the power factor. This equation assumes that the power factor was 1, which did not turn out to be accurate.

Approximately 90% into the experiment, it became evident that there were some major discrepancies in the values obtained by the manufacturers, Roy F. Weston (2) and ourselves.

At this time we went to Reliance Electric Company, a motor manufacturer, and their measurement laboratory manager for technical advice. The difficulty turned out to be the power factor. With the 7.5 hp motors used on the RBC units, the loading was very low. Also, the motors were rated at 460 volts and were running at 480 volts. Both of these items combined to produce a very low power factor which had to be entered into the power equation. With the help of Reliance Electric Co. personnel, a measurement program was established which could be periodically checked with an electronic watt meter.

A round robin testing program was arranged which included representatives of U.S. EPA, Roy F. Weston, Envirex, Reliance Electric and SIECO, Inc. Six shafts were used to measure power, and biomass. Three shafts also were operated at various speeds to measure the change in power requirements for various speeds.

The consensus was that the revised measurement methods used were correct. Power measurements obtained during the last experimental period were the only valid measurements obtained.

LABORATORY ANALYSIS

Laboratory analysis was fairly routine in the types of analyses required, but the number of analyses required was another matter. Due to the daily sampling schedule and the likelihood of both experimental trains running at the same time, up to 12 samples per day could require analysis. These analyses included COD, cBOD (total and soluble), suspended solids, ammonia, nitrite, nitrate and TKN. Not all of these analyses were required daily, however, they did occur frequently enough to necessitate careful scheduling. The acclimation period between the experiments was a welcome relief. This time was used to review the collected data and prepare it for data reduction.

SOLUBLE cBOD - COD

One analytical area which needs to be clarified is the analysis of soluble cBOD and COD. Various attempts have been made to compare cBOD and COD removals with different parameters such as media area, loading rates (both hydraulic and organic) and biomass. It becomes apparent after working with data from fixed-film types of treatment, and for that matter mixed liquor types also, that total cBOD and COD analyses give erratic values. This is probably due to the variance in sloughing of the biomass from the support system and perhaps the difficulty in obtaining a "representative" sample. The variability of the test results makes drawing conclusions from the data difficult. One solution to this problem is to investigate the soluble portion of the sample and monitor its fate as it moves through the treatment system.

Soluble cBOD or soluble COD are terms often encountered in the literature with regard to plant performance. Unfortunately, the term soluble is seldom defined. Therefore, defining soluble, became a priority item for the analysis team during this project.

The analysis team proposed to use the filtrate which was left after suspended solids tests were run. This procedure has the advantage of cutting down some filtering time, especially when both analyses are performed on the same sample. Additionally, the filter which is used is readily available in almost all wastewater laboratories. Thus, a "standard" procedure could be developed which is reproducible in almost any laboratory and can be done by any technician.

A literature review had indicated that various types of filters, ranging from a paper filter to a 0.45 µm membrane filter, have been used for determining the soluble portions of a sample. Each researcher had valid reasoning behind their use of that particular filter (3, 4, 5, 6). Additionally, one member of our technical advisory group suggested that a 0.20 µm filter be used, as it is the standard filter used for sterilzation. With this information in mind, an experimental procedure was set up to investigate the various filters and the soluble cBOD results from each.

The method used was to take a sample of primary effluent and divide it into two portions. One portion was used to determine total cBOD and suspended solids. The other portion was filtered through successively finer, deionized water-washed, filters, (Whatman #1, effective size 11 µm to 0.2 µm) with representative aliquoits of each filtrate retained for cBOD analysis. Samples for the 0.2 µm filtrate were also handled in sterile containers using sterile procedures similar to those used in bacterial analysis. After an initial review of the data obtained from the paper filter, it was decided to concentrate on the smaller porosity filters.

Each aliquoit was then analyzed for cBOD using standard analytical methods (7). One portion of each aliquoit was prepared using seeded dilution water and the normal dilution water. Sterile dilution water was also used with 0.2 µm filtrate in place of the normal dilution water. Both inhibited and non-nitrification inhibited dilutions were included for each sample aliquoit used.

A typical plot of cBOD vs. the filter used is shown in Figure 3. The results indicate a logical trend in that the increasingly finer filters remove more of the suspended materials thus lowering the cBOD analysis. The inhibited samples followed the same trends. Values were lower with the inhibited samples due to the reduction in the oxygen demand by nitrification.

The non-seeded 0.2 µm filtrate results presented some problems. If the 0.2 µm filter was supposed to remove all bacteria, how then was the oxygen depletion showing up? Various theories were put forth ranging from enzymes which passed through the filter, to bacterial contamination. We decided to study the problem by use of standard plate counts (7). We reasoned that if bacteria were found, then the cause would be some type of contamination. The initial results are indicated in Table 1:

TABLE 1. STANDARD PLATE COUNTS FOR VARIOUS SAMPLE FILTRATES AT DAILY INTERVALS

Filtrate	Initial	5 Days Later sterile	5 Days later seeded
0.2 µm filtrate	0	7,700/ml	TNTC*
0.45 µm filtrate	Less than 10/ml	TNTC*	
GF filtrate	145,000/ml	-	
Aerated sterile dilution water	0	-	

*TNTC - too numerous to count.

Additional data were then obtained at one day intervals for representative samples with the results shown in Table 2. The results seem to indicate that the DO depletion is probably due to bacterial contaminations which we were unable to prevent in our laboratory.

Based on the data obtained from parallel evaluation of seeded and non-seeded 0.45 µm filtrate, the experimental procedure established was that of using unseeded glass fiber filtrate (Reeve Angle 934AH) as the sample source for soluble cBOD evaluation. For each experiment a duplicate analysis was performed for one day, using seeded and non-seeded dilution

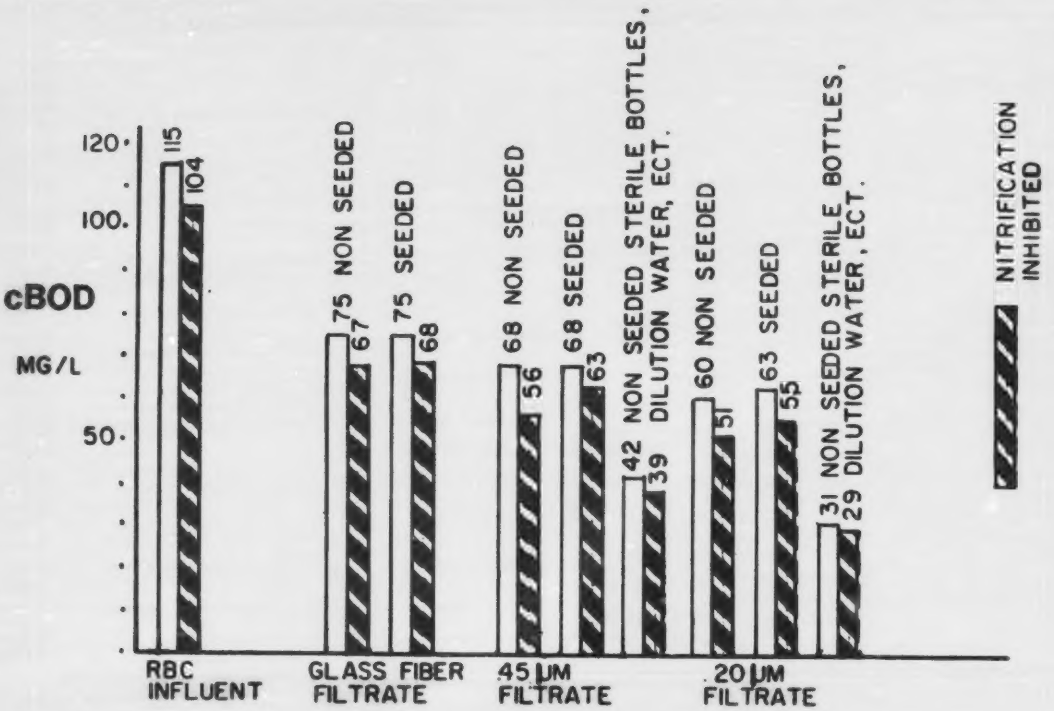


Figure 3. Typical plot of cBOD values versus various filters.

TABLE 2. STANDARD PLATE COUNTS FOR VARIOUS SAMPLE FILTRATES AT DAILY INTERVALS

Day	1	2	3	4	5
Agar	1 colony	--	--	--	0
Dilution water	0/ml	0/ml	0/ml	0/ml	0/ml
Aerated sterile dilution water	0/ml	0/ml	0/ml	0/ml	0/ml
Glass fiber filtrate	246,000/ml	--	--	--	--
0.45 µm filtrate	59/ml	TNTC (low dilution)	52,000,000/ml	16,000,000/ml	--
0.20 µm filtrate	1/ml	4/ml	430/ml	TNTC* (too low dilutions)	TNTC*
Seeded dilution water	138,000/ml	--	--	--	--

*TNTC - Too Numerous to Count.

water. Correlation coefficients in each case were at least 0.9, indicating that the methods were essentially similar.

Nitrification inhibition was used throughout the experiment as the Columbus Wastewater treatment facility was designed to nitrify, especially at the lower flow rates encountered in the initial experiments. The nitrification inhibitor (Hach formula 2533) allowed measurement of only the carbonaceous BOD (7). During each experiment, inhibited and noninhibited samples were set up to check the effects of the inhibitor. In all cases, the inhibited samples showed lower cBOD values than the non-inhibited ones, indicating that some nitrification was taking place even at the highest experimental flow rates.

SECTION 5

EXPERIMENTAL PROCEDURES

PLANT MODIFICATION AND EXPERIMENTAL DESIGN

Following the initiation of the RBC research project in August, 1980, initial study activities were directed toward facility modification design and construction, laboratory and sampling equipment procurement, and experimental design. The plant modification included a pumping facility for controlling flowrates, appropriately placed piping, flow measuring equipment and electrical controls to isolate two RBC bays for the hydraulic and organic loading experimental studies. By September 1981 laboratory equipment had been delivered, automatic sampling equipment had been installed, and all construction was completed.

Experimental design activities included a literature review, data management system development, and initial start-up studies. An extensive review of the scientific and engineering literature on RBC experience and history, with particular attention to hydraulic and organic loading studies of fixed film reactor systems, was completed.

DYE STUDY

An initial start-up mixing study utilizing Rhodamine-B dye to evaluate the hydraulic flow through characteristics in the RBC reactors was completed in August of 1981. Each RBC unit has three inflow gates located parallel to the axis of rotation. Dye was dosed at either one or three of the inflow gates in varying amounts and concentrations, with varying influent flowrates. Data for two representative dye studies are presented in Table 3. Figures 4 and 5 are semi-log plots of dye concentration versus fluid retention time. Such data for an ideal complete-mix reaction would plot as a straight line on semi-log paper.

Observations included the following:

- One to two minutes of retention time were required for mixing in the RBC reactor along the direction of rotation.
- Increased flowrates shortened the retention time of dye in the RBC reactor.
- Increased flowrates did not appear to alter the shape of dye concentration versus retention time plots.
- The RBC reactor seemed to initially follow hydraulic characteristics expected for a complete-mix reactor, but then detained the dye longer than expected. This may be due to slow

TABLE 3. INSTRUMENT CALIBRATION, EXPERIMENTAL PROCEDURES, AND RESULTS OF DYE STUDIES

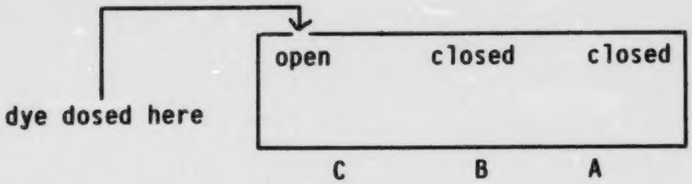
Dye Study A:

Instrument Calibration

Wastewater reading on "x" scale = 1
Blank reading on "x" scale = 1
0 μg/L dye standard on "x" scale = 1
1 μg/L dye standard on "x" scale = 2
3 μg/L dye standard on "x" scale = 5
5 μg/L dye standard on "x" scale = 8
10 μg/L dye standard on "x" scale = 13
25 μg/L dye standard on "x" scale = 26
50 μg/L dye standard on "x" scale = 53

Experimental Procedure

1000 ml of 500 mg/L dye solution was dosed into the hydraulic bay as shown below, with the center inflow gate closed. Sampling sites are shown below. Flowrate = 660 gpm.



Sampling Sites

Results

Cumulative time since injection (min.)	Fluorometer reading on "x" scale Sampling Site A	Sampling Site B	Sampling Site C
0	-	1	-
1	1	14	70
2	1	13	35
3	1	20	21
4	1	18	21
5	1	16	15
7.5	2	12	9
10	2	10	6.5
13	2.5	7.5	5
15	2.5	6	4
20	2	3.5	3
25	2.5	3	2.5
30	2	2.5	2

TABLE 3 (CONTINUED)

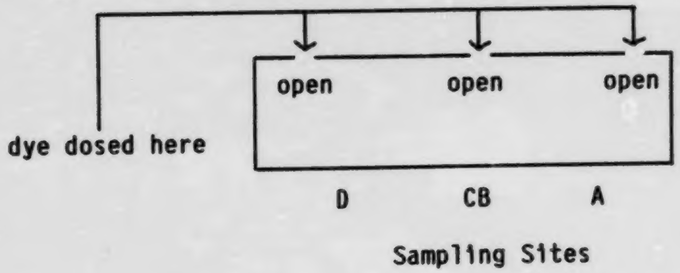
Dye Study B:

Instrument Calibration

0 µg/L dye standard reads 1 on "x" scale
10 µg/L dye standard reads 12 on "x" scale (check = 12)
20 µg/L dye standard reads 25 on "x" scale (check = 23)
30 µg/L dye standard reads 38 on "x" scale (check = 37)
50 µg/L dye standard reads 61 on "x" scale (check = 59)

Experimental Procedure

100 ml. of 5,000 mg/L dye solution was dosed into the hydraulic bay as shown below. Dye was dosed at all three inlet points. Flowrate varied between 320 and 360 gpm. Sites A, C and D were locations where grab samples were collected. A continuous sampler (pump) located at site B collected wastewater from about 2 feet below the surface.



Results

Fluorometer reading on "x" scale

Cumulative time (min.)	Sampling Site A	Sampling Site B (pump)	Sampling Site C	Sampling Site D
0	-	-	-	-
1	23	>100	20	100
2	25	57	32	60
3	32	41	35	47
4	30	34	32	37
5	30	29	28	30
7.5	25	22	21	20
10	20	18	18	15
15	15	12	12	9
20	12	9	9	7
25	10	7	6	6
30	8	6	6	5
40	6	5	4	4

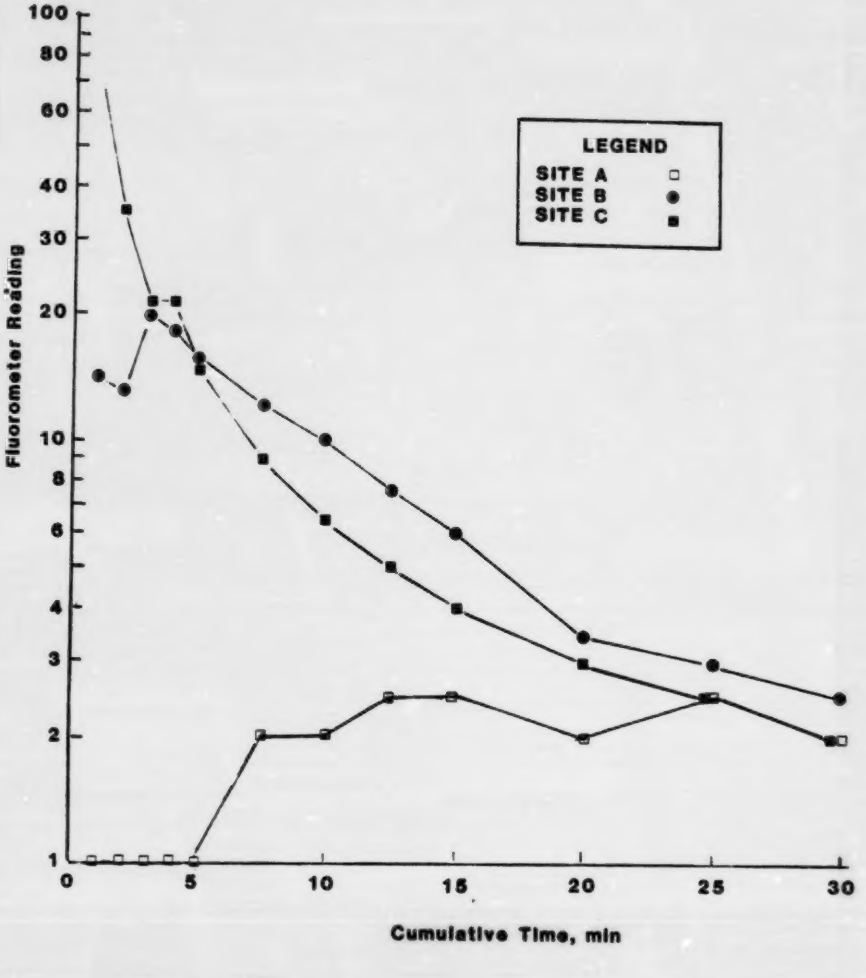


Figure 4. Hydraulic flow characterization: Dye study A.

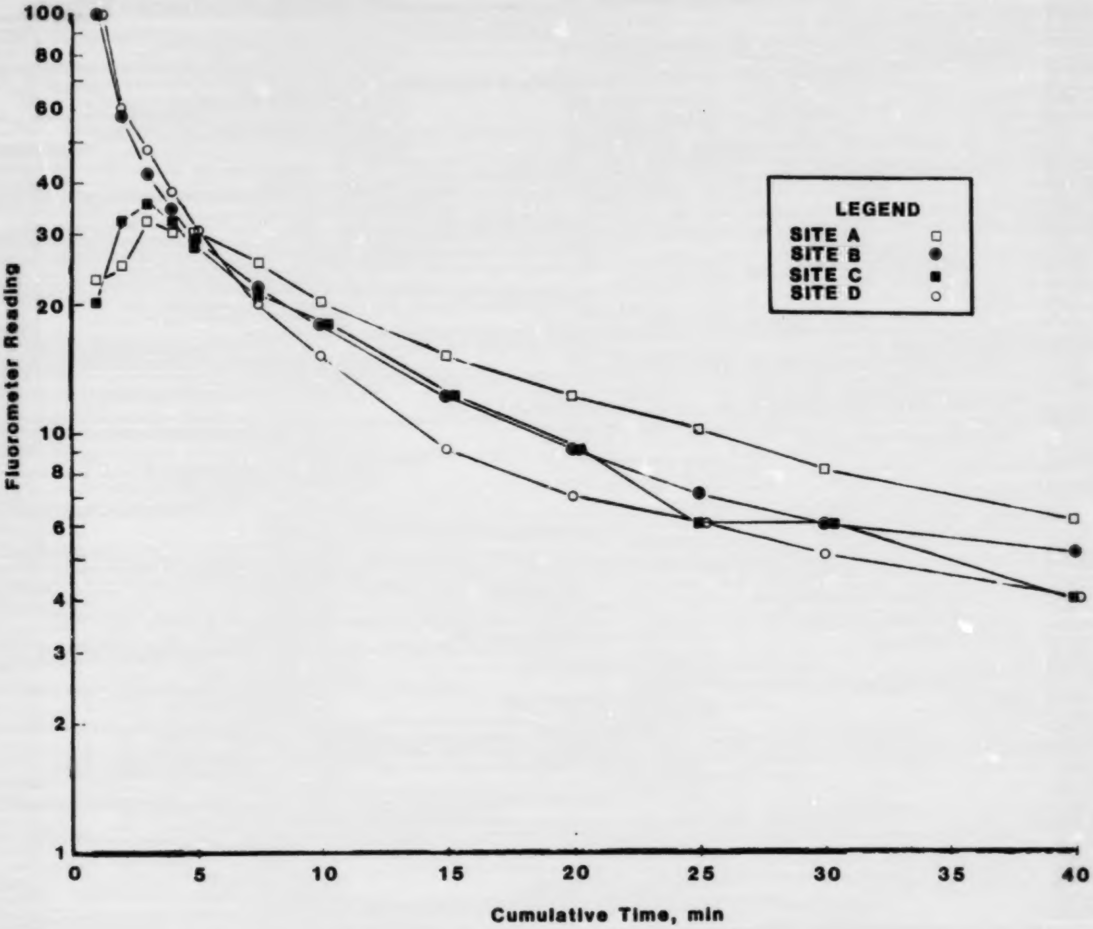


Figure 5. Hydraulic flow characterization: Dye study B.

release of dye from the biomass or walls of the basin, or it may be that RBC units are not completely mixed along the axis of rotation.

Although deviations were observed, it was concluded that the flow characteristics in the RBC units approached hydraulic patterns expected for a completely-mixed reactor system (see Figure 5).

Flowrate

The increase or decrease in either organic or hydraulic loading was obtained by controlling the flowrate pumped to the experimental bays. The plant's design hydraulic loading was 1.6 gallons per day per square foot (gpd/ft^2) of media while the plant's design organic loading was 1.3 pounds of cBOD per 1000 ft^2 of media. Design hydraulic and organic loadings for the experimental bays are shown in Table 4. While loadings to the experimental bays were varied with each flow rate study, the pilot clarifiers operated at a constant surface loading of 640 gpd/ft^2, the design surface loading rate. This was accomplished by the use of a sump pump and throttled bypass, operated such that the flow diverted to the pilot clarifier was constant.

TABLE 4. HYDRAULIC AND ORGANIC LOADINGS FOR FLOW STUDY BAYS

	Hydraulic bay	Organic bay
Number of stages	8	4
Number of shafts	8	8
Media surface area (ft^2)		
Stage		
1	100,000	400,000
2	100,000	200,000
3	100,000	100,000
4	100,000	100,000
5-8	100,000	---
Total	800,000	800,000
Hydraulic loading rate (gpd/ft^2)		
Percent of design flow		
50	0.78	0.78
100	1.6	1.6
200	3.1	3.1
Organic loading rates (lbs. cBOD/1000ft^2)		
Percent of design flow		
50	0.62	0.62
100	1.3	1.3
200	2.5	2.5

SECTION 6

RESULTS AND DISCUSSION

EXPERIMENT DATES

The first flow variation experiment, at 50% design flow (430 gpm), was performed from September 20 to October 14, 1981 with data collection incomplete due to operational start-up problems. Accordingly, no data for this preliminary run were analyzed. Experimental operations were stopped shortly after Experiment 1 because of a delay in project funding. Study efforts began again in February, 1982 and continued through August, 1983, during which time 15 flowrate experiments were performed. Experiment dates and flowrate settings are presented in Table 5. Flowrates ranged in 25% increments from 50% of design flow (430 gpm) to 200% of design flow (1720 gpm). Generally, each experimental run was for a period of two or three weeks with a two-week operational adjustment and system acclimation period between individual studies. Structural failure of shaft 1 in the hydraulic bay necessitated changes in sampling site locations for Experiments 2 through 5. Replacement of this shaft caused a delay during the summer of 1982 before the start of Experiment 6.

FLOWRATE, HYDRAULIC LOADING RATE AND FLUID RETENTION TIME

Flowrate, hydraulic loading rate and fluid retention time data for all hydraulic bay experiments are presented in Table 6. Flowrate was varied from 50% of design flow to 200% of design flow in 25% increments, with experiments at 50%, 75% and 125% of design flow repeated. Hydraulic loading rates ranged from 0.68 gpd/ft^2 at 50% of design flow in Experiment 14 to 3.1 gpd/ft^2 at 200% of design flow in Experiment 9. For Experiments 2 through 5 the hydraulic loading rate was based on a total media surface area of 700,000 ft^2 to account for the broken shaft 1. The broken shaft in stage 1 remained in place during experiments one thru 5 and the flow passed through stage 1. The shaft was replaced after Experiment 5 and the hydraulic bay returned to an 800,000 ft^2 train. Cumulative fluid retention time ranged from 1.0 hours at 200% of design flow to 4.5 hours at 50% of design flow, while the corresponding fluid retention time per stage ranged from 0.13 hours to 0.57 hours.

Flowrate, hydraulic loading rate, and fluid retention time data for organic bay experiments are also presented in Table 6. Flowrate varied from 50% to 200% of the 860 gpm design flow. Experiments were conducted at 25% increments with those at 50%, 75% and 125% of design flow repeated. In addition, two experiments were conducted to evaluate acclimation of nitrifying bacteria. Experiment 12A at 75% of design flow followed

TABLE 5. DATES OF HYDRAULIC AND ORGANIC BAY EXPERIMENTS

Experiment	Bay used	Percent design flow	Starting date	Termination date
1	H,O	50	9/20/81	10/14/81
2	H,O	50	3/07/82	3/27/82
3	H,O	75	4/11/82	5/01/82
4	H,O	100	5/16/82	6/07/82
5	H,O	125	6/20/82	7/09/82
6	H,O	125	9/26/82	10/02/82
7	H	150	10/17/82	10/31/82
8	H	175	11/21/82	12/02/82
9	H	200	12/08/82	12/30/82
10	O	150	1/28/83	2/11/83
11	O	175	2/25/83	3/15/83
12	O	200	3/28/83	4/10/83
12A*	O	75	4/10/83	4/18/83
13	H,O	75	5/11/83	5/24/83
14	H,O	50	6/13/83	6/26/83
14A*	O	200	7/5/83	7/8/83
15**	H	150	7/24/83	10/5/83

H = Hydraulic

O = Organic

*12A was a scale down experiment from 200% to 75% of design flow in order to observe the effect on nitrification. Likewise, 14A was a scale up experiment from 50% to 200% of design flow.

**15 was an experiment designed to study the effects of rotational speed upon performance.

TABLE 6. FLOWRATE, HYDRAULIC LOADING RATE AND FLUID RETENTION TIME FOR HYDRAULIC AND ORGANIC BAY EXPERIMENTS

Experiment	2[a]	3[a]	4[a]	5[a]	6	7	8	9	10	11	12	12A	13	14	14A
Experiment (as percent of design flow)	50	75	100	125	125	150	175	200	150	175	200	75	75	50	200
Experiment Design Flow (gpm)	430	650	860	1080	1080	1290	1510	1720	1290	1510	1720	650	650	480	1720
Experiment Actual Flow (gpm)															
Hydraulic Bay	405	652	860	1075	1046	1294	1500	1720	--	--	--	--	634	380	--
Organic Bay	491	634	873	1060	1056	--	--	--	1270	1477	1695	625	626	381	1641
Hydraulic Loading Rate (gpd/ft^2)															
Hydraulic Bay	0.83[b]	1.34[b]	1.77[b]	2.21[b]	1.88	2.33	2.70	3.06	--	--	--	--	1.14	0.68	--
Organic Bay	0.88	1.14	1.57	1.91	1.90	--	--	--	2.29	2.66	3.05	1.13	1.13	0.69	2.95
Fluid Retention Time For Hydraulic Bay (hr)															
Cumulative	3.72[b]	2.31[b]	1.75[b]	1.40[b]	1.64	1.33	1.15	1.01	--	--	--	--	2.71	4.53	--
Per Stage	0.53	0.33	0.25	0.20	0.21	0.17	0.14	0.13	--	--	--	--	0.34	0.57	--
Fluid Retention Time for Organic Bay (hr)															
Cumulative	3.50	2.71	1.97	1.62	1.63	--	--	--	1.35	1.16	1.01	2.75	2.75	4.51	1.05
Stage 1 only	1.74	1.35	0.98	0.81	0.82	--	--	--	0.68	0.58	0.51	1.38	1.37	2.25	0.52
Stage 2 only	0.88	0.68	0.49	0.41	0.41	--	--	--	0.34	0.29	0.25	0.69	0.69	1.13	0.26
Stage 3 only	0.44	0.34	0.25	0.20	0.20	--	--	--	0.17	0.15	0.13	0.34	0.34	0.57	0.13
Stage 4 only	0.44	0.34	0.25	0.20	0.20	--	--	--	0.17	0.15	0.13	0.34	0.34	0.57	0.13

[a] Stage 1 in the Hydraulic Bay was inoperable during this experiment

[b] Based on total surface area of 700,000 ft^2

[c] Based on 7/8 of cumulative time to account for broken shaft.

immediately after the 200% of design flow experiment. Experiment 14A was run at 200% of design flow immediately after a 50% of design flow experiment. Hydraulic loading rates for the organic bay ranged from 0.69 gpd/ft^2 at 50% of design flow in Experiment 14 to 3.1 gpd/ft^2 at 200% of design flow in Experiment 12. The cumulative fluid retention time varied from 1.0 hours at 200% of design flow to 4.5 hours at 50% of design flow. The fluid retention time by stage ranged from 0.51 hours to 2.3 hours in stage 1 and 0.25 hours to 1.1 hours in stage 2 at 200% and 50% design flow, respectively. The fluid retention time in the third and fourth stages ranged from 0.13 hours at 200% of design flow to 0.57 hours at 50% of design flow.

pH VALUE

Data for pH value by stage of treatment are presented in Table 7 for hydraulic bay experiments. Means were calculated by converting individual pH observations to hydrogen ion concentration, computing their mean, and then converting this mean concentration to a pH value. pH value varied little within the course of an experiment, generally remaining constant throughout all stages or dropping just a few tenths. The only exceptions occurred during both 50% of design flow experiments, when the effluent pH value was slightly higher than the influent pH value. Among all experiments, the various experimental mean pH values observed for a particular stage ranged from 7.0 to 7.7.

The data for instantaneous pH value by stage of treatment for organic bay experiments are presented in Table 8. Observed mean pH values for the experiments varied from 7.2 to 7.7. The pH value of the effluent was 0.1 to 0.3 less than the influent in all experiments except Experiment 14 (50% of design flow) in which it increased by 0.2. The high alkalinity concentration (350 mg/L as $CaCO_3$) in the Columbus wastewater is probably the reason why there was very little reduction in the pH values throughout the study.

WASTEWATER TEMPERATURE

Mean wastewater temperature data by stage of treatment for hydraulic bay experiments are presented in Table 9. The coldest temperatures in the hydraulic bay were observed during Experiment 9 (16°C), which took place in December 1982 (Table 5). The warmest wastewater temperatures were observed during Experiment 5 (23°C, June to July 1982) and Experiment 14 (23°C, June 1983). Of the duplicated flowrate experiments, only those at 50% of design flow were performed with very different wastewater temperatures. Temperatures for Experiment 2 (March 1982) were about 9-10°C lower than those observed during Experiment 14 (June 1983). Temperatures for the two 75% of design flow experiments (Experiments 3 and 13) differed by only 1-2°C, as did wastewater temperatures for the two 125% of design flow experiments (Experiments 5 and 6). Mean wastewater temperatures observed throughout successive stages of a particular experiment remained essentially constant.

TABLE 7. MEAN INSTANTANEOUS pH VALUE BY STAGE OF TREATMENT FOR HYDRAULIC BAY EXPERIMENTS

Experiment	2[a]	3[a]	4[a]	5[a]	6	7	8	9	13	14
Percent design flow	50	75	100	125	125	150	175	200	75	50
Stage of treatment[b]					Mean pH value					
I[c]	7.0	7.7	7.4	7.5	7.5	7.6	7.2	7.3	7.4	7.4
1	7.3	7.7	-	-	7.4	7.5	7.3	7.3	7.4	7.4
2	-	-	7.4	7.4	-	-	-	-	-	-
4	7.1	7.5	7.3	7.4	7.4	7.4	7.2	7.3	7.3	7.3
E[d]	7.5	7.4	7.3	7.4	7.3	7.2	7.2	7.1	7.4	7.6

[a] Stage 1 was inoperable during this experiment

[b] Each stage of Treatment (shaft) contains 100,000 ft^2 of surface area

[c] Influent

[d] Effluent

TABLE 8. MEAN INSTANTANEOUS pH VALUE BY STAGE OF TREATMENT FOR ORGANIC BAY EXPERIMENTS

Experiment	2	3	4	5	6	10	11	12	13	14
Percent design flow	50	75	100	125	125	150	175	200	75	50
Stage of treatment				Mean pH value						
I[a]	7.3	7.7	7.4	7.5	7.5	7.4	7.6	7.4	7.4	7.4
1[b]	7.2	7.5	7.3	7.4	7.4	7.4	7.5	7.3	7.3	7.3
2[c]	-	7.4	7.3	7.3	7.3	7.3	7.4	7.3	7.3	7.5
E[d]	7.2	7.5	7.3	7.4	7.4	7.3	7.3	7.2	7.3	7.6

[a] Influent

[b] Stage 1 contained 400,000 ft^2 of surface area

[c] Stage 2 contained 200,000 ft^2 of surface area

[d] Effluent, Stage 3 and Stage 4 each contained 100,000 ft^2 of surface area prior to sampling the effluent

Mean instantaneous wastewater temperature data by stage of treatment for organic bay experiments are shown in Table 10. The coldest mean influent wastewater temperature observed was 14°C in Experiment 2 (March 1982). Experiment 5 (June to July 1982) had the highest observed temperatures with an influent at 23°C. Temperature variations as great as 4°C between stages were observed in the 50% and 75% of design flow experiments. Experiments 2 and 14 operated at the same flow conditions. The temperature for Experiments 14 was 23°C and showed higher removal rate than Experiment 2 which operated at a temperature of 14°C. Differences in Experiment 2 and 14 performance may be due to temperature. The effect of temperature cannot be established by these data.[4, 5, 6]

DISSOLVED OXYGEN

Mean instantaneous dissolved oxygen concentration by stage of treatment for hydraulic bay experiments is presented in Table 11. At all flowrates a marked decline in dissolved oxygen concentration was seen from the influent through stage 4. Influent concentrations varied from 2.7 to 5.0 mg/L, while those at stage 4 ranged from 0.35 to 3.1 mg/L. Generally the lowest concentration observed during an experiment occurred at stage 4. Dissolved oxygen concentrations recovered by stage 8 for all flowrates except the 175% and 200% of design flow experiments, when the lowest concentrations were observed at stage 8 and the system never recovered. In contrast, dissolved oxygen concentrations at stage 8 of the two 50% of design flow experiments were the highest observed (5.8 and 6.2 mg/L), even higher than influent concentrations.

The mean instantaneous dissolved oxygen data by stage of treatment are presented in Table 12 for organic bay experiments. Generally, the oxygen concentration was highest in the influent and lowest in stage 1. The 50% of design flow experiments increased dissolved oxygen in the effluent above the level in the influent. In Experiment 14 at 50% of design flow the dissolved oxygen concentration increased in each stage of treatment. At 200% of design flow the dissolved oxygen concentration continued to drop in each stage. The lowest levels of dissolved oxygen were observed at 125% of design flow in Experiments 5 and 6. These experiments were conducted in July and August of 1982 when wastewater temperatures were high (Table 10) and influent dissoved oxygen levels were at their lowest values (Table 12). The highest experimental dissolved oxygen concentrations recorded were 4.5 and 5.3 mg/L at stage 4 in the 50% of design flow experiments.

PSEUDO OXYGEN TRANSFER RATE

Pseudo oxygen transfer rates were calculated based on mean soluble cBOD and mean soluble COD removals across the first and second stages. (An example calculation is presented in Appendix B.) As shown in Table 13, for hydraulic bay stage 1 the rates calculated from cBOD removals varied from 20 mg O_2/hr/ft^2 at 50% and 75% of design flow to 41 mg O_2/hr/ft^2 at 150% of design flow. First stage transfer rates based on COD removal ranged from 24 mg O_2/hr/ft^2 at 200% of design flow to 59 mg O_2/hr/ft^2 at 125% of design flow. For stage 2 the range based on cBOD removals was from 4 mg O_2/hr/ft^2 at 50% of design flow to 14-15 mg O_2/hr/ft^2 at 100%,

TABLE 9. MEAN INSTANTANEOUS WASTEWATER TEMPERATURE BY STAGE OF TREATMENT FOR HYDRAULIC BAY EXPERIMENTS

Experiment	2	3	4	5	6	7	8	9	13	14
Percent design flow	50	75	100	125	125	150	175	200	75	50
Stage of treatment	Mean wastewater temperature, °C									
I	14	18	22	23	22	21	18	16	20	23
1	15	17	-	-	22	21	18	16	19	23
2	-	-	22	23	-	-	-	-	-	-
4	14	18	22	23	22	21	18	16	19	23
E	13	18	22	24	22	21	18	16	19	23

TABLE 10. MEAN INSTANTANEOUS WASTEWATER TEMPERATURE BY STAGE OF TREATMENT FOR ORGANIC BAY EXPERIMENTS

Experiment	2	3	4	5	6	10	11	12	13	14
Percent design flow	50	75	100	125	125	150	175	200	75	50
Stage of treatment	Mean Wastewater Temperature, °C									
I	14	18	22	23	22	14	16	16	20	19
1	15	18	22	23	22	14	16	16	19	23
2	-	18	22	23	22	14	17	16	19	23
E	13	18	22	24	22	14	17	16	23	23

TABLE 11. MEAN INSTANTANEOUS DISSOLVED OXYGEN BY STAGE OF TREATMENT FOR HYDRAULIC BAY EXPERIMENTS

	Mean concentration of dissolved oxygen, mg/L				
Experiment	Influent	Stage 1	Stage 2	Stage 4	Stage 8
2[a]	5.0	4.8	-	3.1	5.8
3[a]	3.4	3.7	-	0.6	0.8
4[a]	3.5	-	1.8	0.6	1.2
5[a]	3.5	-	1.8	0.6	0.8
6	3.2	1.7	-	0.4	0.8
7	3.8	2.3	-	0.8	1.0
8	3.9	3.2	-	1.5	1.4
9	4.5	4.0	-	2.3	1.4
13	3.4	1.4	-	1.1	3.3
14	2.7	0.7	-	1.6	6.2

[a] Shaft 1 was inoperable during this experiment

TABLE 12. MEAN INSTANTANEOUS DISSOLVED OXYGEN BY STAGE OF TREATMENT FOR ORGANIC BAY EXPERIMENTS

	Concentration of dissolved oxygen mg/L,			
Experiment[a]	Influent	Stage 1	Stage 2	Stage 4
2	5.0	3.1	4.1	4.5
3	3.4	1.3	1.5	1.6
4	3.5	0.9	1.3	1.2
5	3.4	0.6	0.8	0.9
6	3.3	0.6	0.6	0.7
10	3.3	1.0	2.4	1.8
11	3.9	0.8	1.1	0.8
12	4.9	1.4	1.1	1.0
12A	3.1	--	--	--
13	3.4	1.9	2.5	3.2
14	2.7	3.1	4.6	5.3

[a] Dissolved oxygen was not measured for Experiment 14A

125% and 150% of design flow. Using COD removals, the range was from 7 mg O_2/hr/ft^2 at 50% of design flow to 46 mg O_2/hr/ft^2 at 125% of design flow. The first stage always had higher pseudo oxygen transfer rates, based both on cBOD and COD removals, than the second stage. Transfer rates based on COD removals were usually higher than those based on cBOD removals.

The calculated pseudo oxygen transfer rates across the first and second stage of treatment of the organic bay are presented in Table 14. The pseudo oxygen transfer rates were also calculated from the mean soluble cBOD and soluble COD removals across the first two stages. However, stages 1 and 2 of the organic bay contain 400,000 and 200,000 ft^2 of surface area, respectively, as compared with 100,000 ft^2 in each of the first two stages of the hydraulic bay. For stage 1 the rates calculated from the soluble cBOD removal varied from 7.3 mg O_2/hr/ft^2 at 50% of design flow to 18 mg O_2/hr/ft^2 at both 175% and 200% of design flow. The pseudo oxygen transfer rates for the first stage based upon COD removal ranged from 13 mg O_2/hr/ft^2 at 75% of design flow to 49 mg O_2/hr/ft^2 at 200% of design flow. For stage 2 the range based on cBOD was from 0.3 to 21 mg O_2/hr/ft^2 for 50% and 200% of design flow experiments respectively. Using COD to calculate the stage 2 pseudo oxygen transfer rate, the range was from 2.6 mg O_2/hr/ft^2 at 50% of design flow (Experiment 14) to 49 mg O_2/hr/ft^2 at 175% of design flow. The first stage usually had higher pseudo oxygen transfer rates than the second stage. Only Experiments 11 and 12 had higher calculated oxygen transfer in stage 2 based on COD and cBOD, respectively.

SUSPENDED SOLIDS AND VOLATILE SUSPENDED SOLIDS

Table 15 presents the mean suspended solids data for hydraulic bay experiments. The effluent values were reported for the effluent from the pilot clarifier. The mean influent suspended solids concentration for the various experiments ranged from 58 mg/L to 122 mg/L. Experimental mean volatile suspended solids varied from a low of 47 mg/L in the influent to a high of 95 mg/L. There was no discernable trend in suspended solids or volatile suspended solids concentrations.

In Table 16 the mean suspended solids data for the various organic bay experiments are presented. Mean suspended solids data did not show any apparent trend. Likewise, the mean volatile suspended solids data did not show any apparent trends with flowrate or stage of treatment.

BIOMASS WEIGHT AND THICKNESS

Mean shaft biomass weight and biomass thickness for the hydraulic bay and organic bay experiments are presented in Table 17. Biomass always decreased through successive stages of the hydraulic bay. For stage 1 biomass ranged from 20,500 pounds and 58 mils (1.5 mm) thick at 125% of design flow to 33,000 pounds and 90 mils (2.3 mm) thick at both 75% and 125% of design flow. In the fifth stage, biomass varied from 11,800 pounds and 33 mils (0.8 mm) at 50% of design flow to 25,000 pounds and 68 mils (1.7 mm) thick at 200% of design flow. For stage 7, the range was from 7,900 pounds and 21 mils (0.5 mm) at 50% of design flow to 24,000 pounds and 67 mils (1.7

TABLE 13. CALCULATED PSEUDO OXYGEN TRANSFER RATES FOR HYDRAULIC BAY EXPERIMENTS

Experiment	Percent of design flow	Flowrate (gpm)	cBOD removal[a], mg/L		COD Removal[a], mg/L		Pseudo transfer rate, mg O_2/hr/ft^2			
			across	across	across	across	cBOD		COD	
			1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage
2	50	405	21	8	31	18	20	7	30	17
3	75	652	13	9	24	19	20	13	36	28
4	100	860	12	8	21	17	24	15	42	33
5	125	1,075	14	6	24	11	34	14	59	26
6	125	1,046	16	6	18	19	39	14	44	46
7	150	1,294	14	5	15	4	41	14	45	11
8	175	1,500	7	2	11	7	24	6	38	24
9	200	1,700	9	2	6	6	36	7	24	23
13	75	634	19	4	29	9	27	6	42	13
14	50	380	27	4	57	8	23	4	49	7

[a] In Experiments 2-5 shaft 1 was inoperable and the removals across stage 2 and stage 3 were used for these calculations.

TABLE 14. CALCULATED PSEUDO OXYGEN TRANSFER RATES FOR ORGANIC BAY EXPERIMENTS

Experiment	Percent of design flow	Flowrate (gpm)	cBOD removal, mg/L across		COD removal, mg/L across		Pseudo oxygen transfer rate, mg $O_2/hr/ft^2$ cBOD		Pseudo oxygen transfer rate, mg $O_2/hr/ft^2$ COD	
			1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage
2	50	491	29	5.7	51	17	8.1	3.2	14	9.4
3	75	634	31	5.5	56	10	11	4.0	20	7.5
4	100	873	27	6.5	52	14	14	6.4	26	14
5	125	1,060	27	9.1	53	14	16	11	32	16
6	125	1,056	27	8.9	49	17	16	11	29	21
10	150	1,270	23	6.5	48	20	17	9.4	35	28
11	175	1,477	21	7.9	35	29	18	13	29	49
12	200	1,695	19	11	51	16	18	21	49	30
13	75	626	28	4.5	38	15	10	1.6	13	5.3
14	50	381	34	1.5	69	12	7.3	0.3	15	2.6

[a] Experiments 12A and 14A were not included due to their experimental design

TABLE 15. MEAN SUSPENDED SOLIDS AND VOLATILE SUSPENDED SOLIDS FOR HYDRAULIC BAY EXPERIMENTS

Experiment	2	3	4	5	6	10	11	12	13	14
Percent design flow	50	75	100	125	125	150	175	200	75	50
Stage of treatment	Mean suspended solids, mg/L									
I	106	89	76	87	66	68	58	73	88	122
5	-	129	83	102	-	-	-	-	-	-
6	85	106	93	120	55	64	46	48	99	127
7	85	106	93	120	55	64	46	48	99	127
E	27	43	30	34	18	39	30	23	12	16
	Mean volatile suspended solids, mg/L									
I	70	67	63	68	55	49	47	57	69	95
5	-	91	67	82	-	-	-	-	-	-
6	61	-	-	-	52	72	37	34	75	93
7	59	72	77	97	47	46	39	38	75	97
E	17	29	24	26	14	28	25	20	10	12

TABLE 16. MEAN SUSPENDED SOLIDS AND VOLATILE SUSPENDED SOLIDS FOR ORGANIC BAY EXPERIMENTS

Experiment	2	3	4	5	6	10	11	12	13	14
Percent design flow	50	75	100	125	125	150	175	200	75	50
Stage of treatment	Mean suspended solids, mg/L									
I	106	89	76	87	66	78	86	79	88	122
1	-	-	-	-	-	83	80	92	-	-
2	-	-	-	-	-	64	66	69	-	-
3	164	106	130	110	75	78	69	74	99	92
E	46	28	25	28	13	17	20	31	30	16
	Mean volatile suspended solids, mg/L									
I	70	67	63	68	55	59	70	63	69	95
1	-	-	-	-	-	67	64	77	-	-
2	-	-	-	-	-	53	54	57	-	-
3	107	77	103	92	59	64	57	58	77	70
E	33	21	21	25	11	14	17	26	24	12

mm) at 200% of design flow. It was difficult to discern a relationship between biomass and flowrate. For stages 5 and 7 biomass weight appeared to increase with increasing flowrate, while for stage 1 no such trend was evident.

Instage 1 of the organic bay experiments, the biomass ranged from 13,000 lbs and 35 mils (0.9 mm) thick at 125% of design flow to 29,400 lbs and 80 mils (2.0 mm) thick at 175% of design flow. In the second stage of treatment, the biomass varied from 12,000 lbs and 32 mils (0.8 mm) in thickness to 29,600 lbs and 80 mils (2.0 mm) in thickness at 50% and 175% of design flow, respectively. Likewise, the biomass on the third shaft ranged from 8,000 lbs and 20 mils (0.5 mm) at 50% of design flow to 26,300 lbs and 70 mils (1.8 mm) at 150% of design flow.

A different load cell gauge was used beginning with Experiment 10 but the observed differences in biomass between the duplicate experiments at 50% and 75% of design flow were not great. The greater biomass observed at flows equal to or greater than 125% of design flow may be the result of factors other than the new load cell gauge. Differences in wastewater temperature, dissolved oxygen concentrations and other experimental conditions may be responsible for the measured differences in biomass weight.

cBOD AND COD REMOVAL

The design of the research program was to conduct a side-by-side comparison of the treatment performance of the hydraulic and organic bays under flow variations between 50 to 200% of the design flowrate. Side-by-side evaluations were completed for the 50%, 75%, 100% and 125% flow condition. Unfortunately, a side-by-side comparison could not be completed for the 150%, 175%, and 200% design flowrates, because a limited volume of wastewater was available during this period of the research project. Evaluations of the hydraulic and organic bays at the 150%, 175%, and 200% flow condition were therefore completed independently of one another. As such, the experimental conditions that existed during the completion of these later experiments varied somewhat between the hydraulic and organic bays. Information about the time periods when each experiment was completed and associated experimental conditions were discussed previously.

Influent BOD and Organic Loading Conditions

Figure 6 contains information about the flowrate, influent mean soluble cBOD concentration, and influent soluble cBOD mass loading rate that existed for each of the hydraulic bay experiments. As shown in the middle graph of Figure 6, Experiment 8 (175% of design flow) and Experiment 9 (200% of design flow) had a low influent mean soluble cBOD concentration resulting in an unexpected low cBOD mass loading rate during these two experiments. This effect can be seen clearly in the lower graph of Figure 6, where the mass loading rate for Experiment 8 was less than that for the Experiment 7 (150% design flowrate experiment). As shown in this same figure, the soluble cBOD mass loading rate in Experiment 7 and Experiment 9 was nearly equal, even though the flowrates in these two experiments were substantially different.

TABLE 17. BIOMASS DATA FOR HYDRAULIC AND ORGANIC EXPERIMENTS

Experiment	2[a]	3[a]	4[a]	5[a]	6	7	8	9	10[b]	11[b]	12[b]	12A[bc]	13[b]	14[b]	14A[bd]
Percent design flow	50	75	100	125	125	150	175	200	150	175	200	75	75	50	200
							Mean shaft biomass, lbs x 10^3								
Bay - Stage															
Hydraulic - 1[e]	-	33	32	33	21	22	23	28	-	-	-	-	27	22	-
Hydraulic - 5	18	-	-	-	19	20	20	25	-	-	-	-	15	12	-
Hydraulic - 7	8	9	13	12	17	19	20	24	-	-	-	-	10	9	20
Organic - 1	17	17	19	17	13	-	-	-	29	29	29	28	21	19	20
Organic - 2	23	17	16	16	17	-	-	-	29	30	29	29	17	12	14
Organic - 3	13	10	15	16	13	-	-	-	26	25	23	24	12	8	11
							Biomass thickness, mils[f]								
Bay - Stage															
Hydraulic - 1[e]	-	90	85	90	58	60	62	77	-	-	-	-	73	60	-
Hydraulic - 5	49	-	-	-	50	54	54	68	-	-	-	-	42	33	-
Hydraulic - 7	21	25	35	38	48	50	51	67	-	-	-	-	27	23	-
Organic - 1	46	45	52	46	35	-	-	-	78	80	78	75	57	52	55
Organic - 2	65	46	42	40	42	-	-	-	82	80	75	80	45	32	40
Organic - 3	34	27	38	40	38	-	-	-	70	70	63	65	32	20	30

[a] Stage 1 in the hydraulic bay was inoperable during this experiment

[b] After Experiment 9 a new load cell reading instrument was used

[c] Cumulative day number 4

[d] Cumulative day number 3

[e] Measured on shaft 2 for experiments 2 through 5

[f] One mil equals 0.001 inches

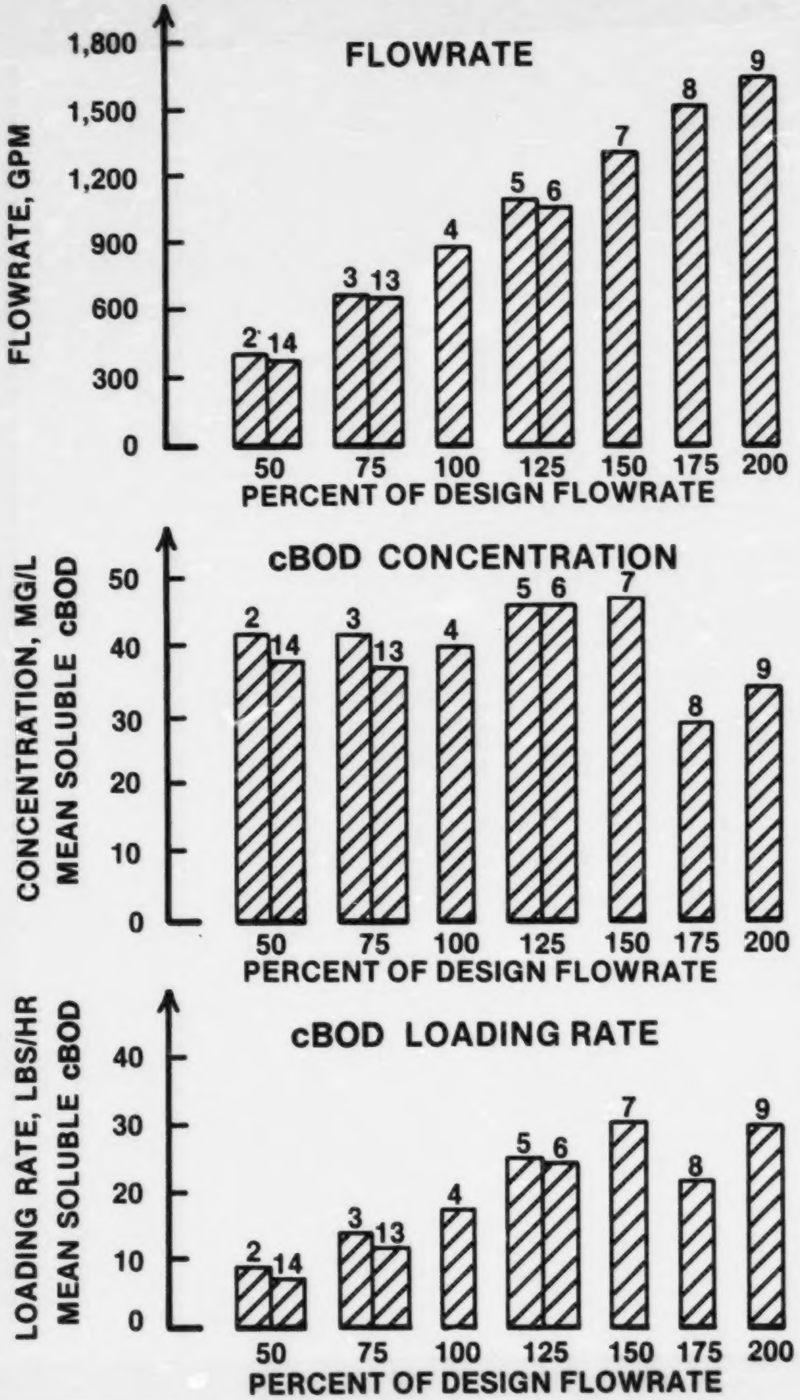


Figure 6. Wastewater flowrate and influent mean soluble cBOD concentration and loading rate for hydraulic bay experiments.

Information about the influent conditions to the organic bay are shown in Figure 7. The organic bay experiments did not have an erratic variation in the influent mean soluble cBOD concentrations and, as such, the soluble cBOD mass loading rate increased with increased flowrate applied (see lower graph in Figure 7). The influent mean soluble cBOD for the various experiments ranged from a low of 37 mg/L in Experiment 13 to a high of 46 mg/L in Experiments 5 and 6. The soluble cBOD loading rate was lowest for the 50% design flow experiment (Experiment 14) and highest for the 200% design flow experiment (Experiment 12). The mass loading rates for these two experiments were 7 and 37 pounds soluble cBOD per hour, respectively.

Soluble cBOD and COD mass loading rates applied to the organic and hydraulic treatment bays are shown in Table 18. In this table, data are shown for the first stage of treatment, as well as for the overall treatment train. The unit of expression used in this table is pounds of soluble cBOD applied per day per 1,000 ft^2 of media surface area (i.e., lbs cBOD/day/1,000 ft^2). The soluble cBOD information given in Table 18 is reorganized in Tables 19 and 20 to facilitate comparing experimental conditions for the organic and hydraulic bay studies.

Table 19 presents the soluble cBOD mass loading rates, based on all stages of treatment, for both the hydraulic and organic bays at varying flowrate conditions. It is important to note that the mass loading rate is fairly constant between the organic and hydraulic bays for those experiments where the two treatment bays were compared on a side-by-side basis. This is not the case for the 150%, 175% and 200% of design flow experiments, however. Table 19 illustrates that a considerably higher soluble cBOD mass loading rate was applied to the organic bay in the 175% and 200% design flow experiments, in comparison to the hydraulic bay. In the 150% design flow experiments, the opposite loading condition existed with the hydraulic bay receiving the higher organic loading rate. It is important to keep these differences in cBOD mass loadings rates in mind to properly evaluate the comparative performance of the two treatment bays. This is especially necessary for the 150, 175, and 200% flowrate experiments which were not conducted on a side-by-side basis.

One of the major advantages of the organic bay flow scheme is the ability to lower the organic loading rate applied during early stages of treatment. At the Columbus RBC research facility, this was accomplished by having 400,000 ft^2 and 200,000 ft^2 of media surface area in the first and second stages of treatment, respectively. The effect of this modification to the applied soluble cBOD loading rate can be seen in Table 20, which lists comparative statistics for the hydraulic versus organic bay at the various flowrate conditions studied. It is noteworthy that the cBOD mass loadings applied to stage 1 of the organic bay did not exceed EPA's design guideline of 2.5 lbs soluble cBOD/day/1,000 ft^2 in any of the organic bay experiments. In comparison, it can be seen in Table 20 that EPA's guideline was exceeded in the first stage of the hydraulic bay for every experiment, except the 50% design flowrate experiment.

The ability of the organic bay flow scheme to distribute the organic loading equally among stages can be seen in Figure 8, which depicts the

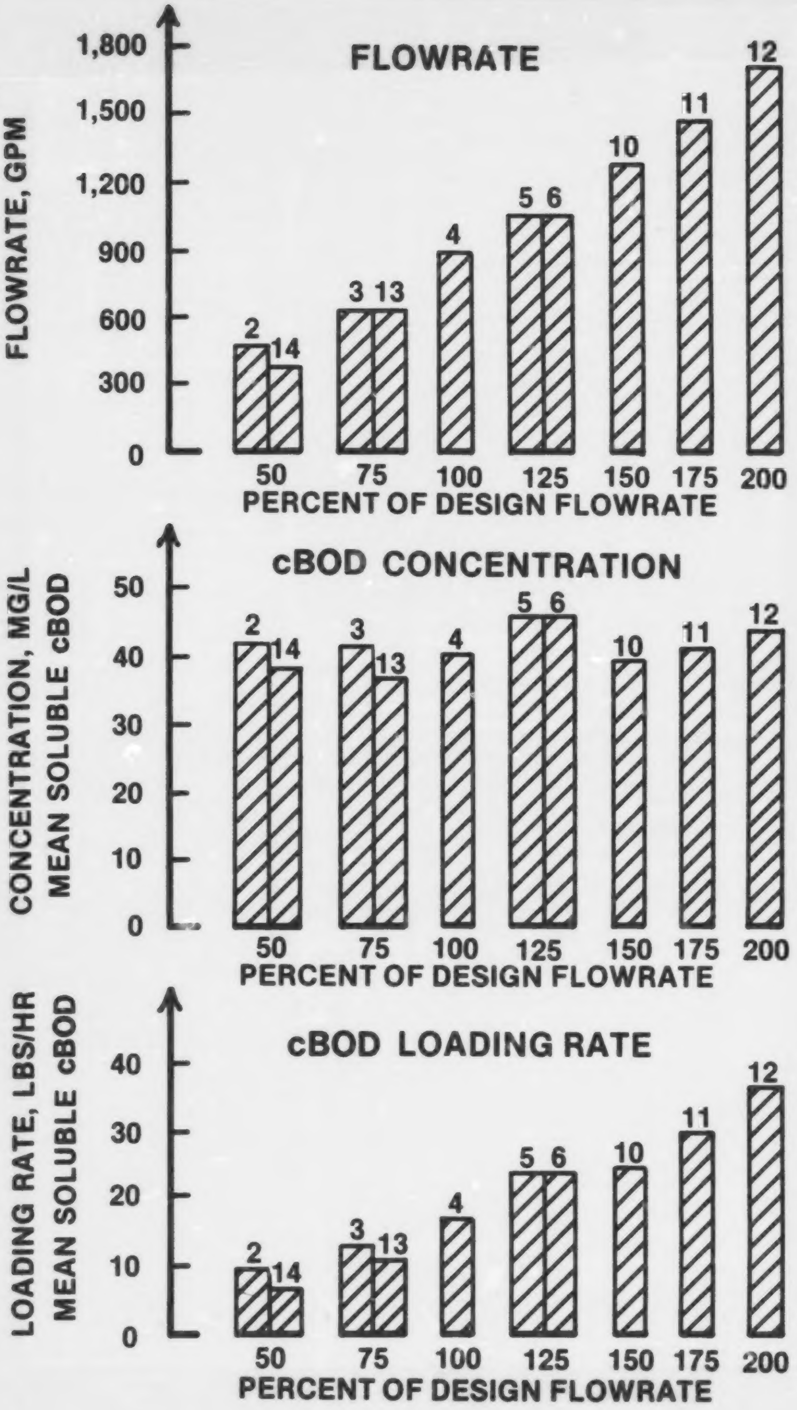


Figure 7. Wastewater flowrate and influent mean soluble cBOD concentration and loading rate for organic bay experiments.

TABLE 18. SOLUBLE cBOD AND SOLUBLE COD LOADING RATES FOR HYDRAULIC AND ORGANIC BAY EXPERIMENTS

Experiment		2^a	3^a	4^a	5^a	6	7	8	9	10	11	12	12A	13	14	14A
Percent design flow		50	75	100	125	125	150	175	200	150	175	200	75	75	50	200
						Soluble cBOD loading rate, lbs cBOD/day/1000ft^2										
Hydraulic Bay -	all stages	0.29^b	0.47^b	0.59^b	0.85^b	0.72	0.91	0.65	0.87	--	--	--	--	0.35	0.22	--
	Stage 1^c	2.0	3.3	4.1	6.0	5.8	7.3	5.2	7.0	--	--	--	--	2.6	1.8	--
Organic Bay -	all stages	0.31	0.40	0.52	0.73	0.73	--	--	--	0.74	0.91	1.1	0.25	0.35	0.22	1.0
	Stage 1^d	0.62	0.80	1.0	1.5	1.5	--	--	--	1.4	1.8	2.2	0.50	0.70	0.44	2.1
						Soluble COD loading rate, lbs COD/day/1000ft^2										
Hydraulic Bay -	all stages	0.75b	1.3b	1.6b	2.1b	1.8	1.9	1.9	2.6	--	--	--	--	0.91	0.67	--
	Stage 1	5.3	9.1	11.1	14.8	14.2	15.4	15.5	20.8	--	--	--	--	7.3	5.4	--
Organic Bay -	all stages	0.79	1.1	1.4	1.9	1.8	--	--	--	2.4	3.0	3.5	0.90	0.90	0.67	2.2
	Stage 1	1.6	2.2	2.8	3.7	3.6	--	--	--	4.8	5.9	6.9	1.8	1.8	1.3	4.3

[a] Shaft 1 in the hydraulic bay was inoperable during this experiment

[b] Based on total surface area of 700,000 ft^2

[c] Stage 1 in the hydraulic bay contains 100,000 ft^2 of surface area

[d] Stage 1 in the organic bay contains 400,000 ft^2 of surface area

TABLE 19. COMPARISON OF SOLUBLE cBOD MASS LOADING RATE FOR ORGANIC AND HYDRAULIC BAYS FOR ALL STAGES OF TREATMENT

Percent of design flowrate	Mass loading rate, lbs cBOD /day/1,000 ft^2	
	Hydraulic bay	Organic bay
50[a]	0.27[b,c]	0.26[b]
75[a]	0.39[b,c]	0.38[b]
100[a]	0.59[c]	0.52
125[a]	0.77[b,c]	0.73[b]
150	0.91	0.74
175	0.65	0.91
200	0.87	1.1

[a] side-by-side evaluation

[b] average of two replicate experiments

[c] average after 700,000 ft^2 and 800,000 ft^2 of treatment

TABLE 20. COMPARISON OF SOLUBLE cBOD MASS LOADING RATE FOR ORGANIC AND HYDRAULIC BAYS FOR THE FIRST STAGE OF TREATMENT

Percent of design flowrate	Mass loading rate, lbs cBOD /day/1,000 ft^2	
	Hydraulic bay	Organic bay
50[a]	1.9[b,c]	0.5[b]
75[a]	2.9[b,c]	0.7[b]
100[a]	4.1[c]	1.0
125[a]	5.9[b,c]	1.5[b]
150	7.3	1.4
175	5.2	1.8
200	7.0	2.2

[a] side-by-side evaluation

[b] average of two replicate experiments

[c] average of 700,000 and 800,000 ft^2 of treatment

organic loading rate versus stage of treatment for both the hydraulic and organic treatment bays. Information for Experiment 4 (100% design flow) and Experiments 8 and 11 (175% design flow) are given in Figure 8 to illustrate how the organic loading rate varied under an average and high flowrate condition. Note especially in Figure 8 the ability of the organic bay's flow configuration to maintain a relatively constant organic loading rate at each stage of treatment and that the actual organic loading rate met EPA's guideline. In contrast, the organic loading rate in the hydraulic bay exceeded the EPA guidelines in many of the earlier stages of treatment. In summary, the organic flow scheme allows for an equalization of the organic load between stages and helps to avoid many of the problems which have been found to occur when RBC shafts are organically overloaded. Such conditions include: (a) excessive biomass growth, with possible structural failures; (b) low oxygen or anoxic conditions; (c) undesirable odors; (d) nuisance organisms; and (e) poor cBOD removal performance.

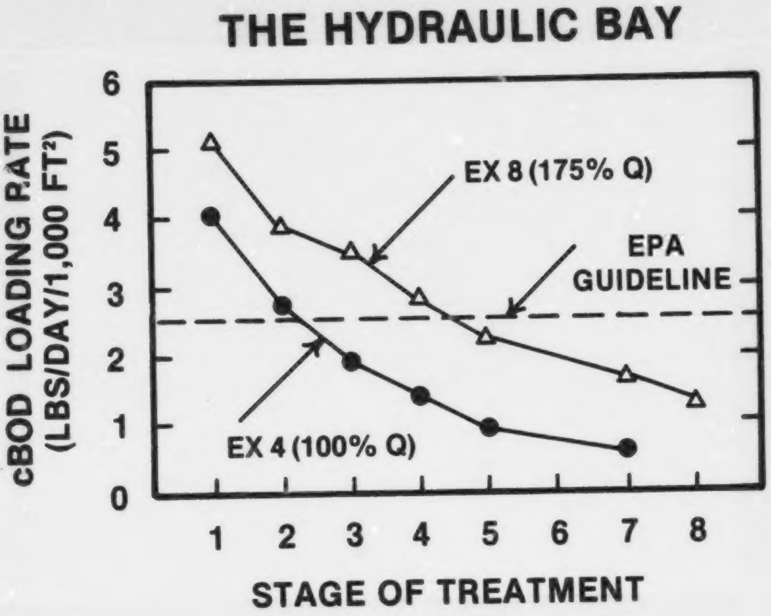
Total cBOD removal

As illustrated in Table 21 the total cBOD removal by both the hydraulic and organic bays was quite impressive throughout the duration of the study. The increasing flow rate did not significantly influence the treatment ability of the two flow schemes as demonstrated by the relatively stable removal efficiencies for the 50 to 175% design flow experiments. When the flow was increased to the 200% design flow level, there was some deterioration in effluent quality which was probably due to the reduced residence time in the treatment bays. The higher flow rate could have also caused increased shearing of biological slime from the RBC's thus increasing the suspended solids in the effluent and consequently the reduced total cBOD removal efficiencies.

Overall Soluble cBOD Removal

Information on the mean concentration of soluble cBOD entering and leaving the RBC treatment bays is listed in Table 22. The values recorded for the effluent are after all RBC treatment and pilot sedimentation were completed. The mean soluble cBOD concentration for the various experiments in the influent to the experimental bays ranged between 29-47 and 26-46 mg/L for the hydraulic and organic bays, respectively. As shown in Table 22, both treatment bays were capable of consistently reducing the influent cBOD to less than 10 mg/L. Effluent levels as low as 2-4 mg/L were achieved in the effluent from both the organic and hydraulic bays at flowrates less than 100% of the design flowrate. In general, levels of soluble cBOD in the effluent increased with increased flowrate. The highest effluent mean soluble cBOD concentration for the hydraulic bay was 9.2 mg/L, which occurred in Experiment 9 (200% design flow). Similarly, the organic bay's highest, effluent mean soluble cBOD concentrations was 8.3 mg/L, which was monitored for Experiment 12 (200% flow also).

The percent removal of mean soluble cBOD for each experiment completed is also shown in Table 22. These data are plotted in Figure 9 and rearranged in Table 23 for ease of interpretation. Three observations are



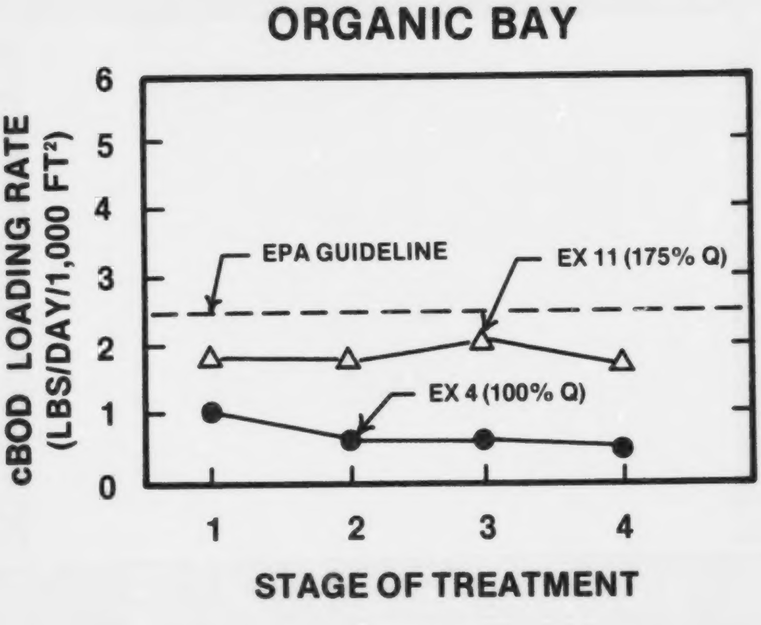


Figure 8. Comparison of mean soluble cBOD loading rate for selected experiments for the hydraulic and organic bays.

TABLE 21. COMPARISON OF TOTAL cBOD REMOVAL IN THE HYDRAULIC AND ORGANIC BAY EXPERIMENTS

Percent of design flowrate	Percent removal of total cBOD	
	Hydraulic bay	Organic bay
50[a]	83[b,c]	79[b]
75[a]	83[b,c]	85[b]
100[a]	83[c]	85
125[a]	83[b,c]	85[b]
150	73	82
175	83	80
200	67	72

[a] side-by-side evaluation

[b] average of two replicate experiments

[c] based on average of 700,000 and 800,000 ft^2 of treatment

noteworthy. First, a high level of cBOD removal was accomplished in both the organic and hydraulic treatment bays. Percent removals as high as 89-92% were achieved in both bays for the 50-100% design flow experiments. Second, the percent removal of soluble cBOD dropped as the flowrate was increased. This observation was apparent for both the hydraulic and organic treatment bays. Third, with one exception there does not appear to be any practical difference between the percent removals recorded for the organic bay versus that accomplished by the hydraulic bay. This later statement applies to the comparison of the influent and effluent cBOD concentrations to the entire treatment bays (i.e. for 800,000 ft^2 of treatment).

In Figure 9, it can be seen that the soluble cBOD removals for the 200% design flow experiments differ considerably. Specifically, the organic bay reduced the influent mean soluble cBOD from 44 mg/L to 8.3 mg/L after 800,000 ft^2 of treatment for an 81% reduction. In the 200% flow hydraulic bay experiment, the influent cBOD was 34 mg/L with an effluent value of 9.2 mg/L. This corresponds to a 73% reduction for the hydraulic bay. The lower influent cBOD concentration to the hydraulic bay is thought to be responsible for the extremely low cBOD percent removal noted for this experiment. The rate of substrate removal within the RBC bays appears to follow second order kinetics and, therefore, the rate of removal of cBOD is highly dependent on the concentration of cBOD entering the treatment bays.[11]

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TABLE 22. COMPARISON OF SOLUBLE AND TOTAL cBOD REMOVALS IN THE HYDRAULIC AND ORGANIC BAY EXPERIMENTS

Experiment	Percent design flow	Mean soluble cBOD			Mean total cBOD		
		I (mg/L)	E (mg/L)	Removed (%)	I (mg/L)	E (mg/L)	Removed (%)
Hydraulic bay							
2	50	43	4.2	89	89	23	74
14	50	38	2.2	94	85	6	93
3	75	42	5.6	87	95	24	75
13	75	37	3.5	90	73	5	93
4	100	40	4.5	89	82	14	83
5	125	46	8.3	82	82	17	79
6	125	46	7.9	83	78	11	86
7	150	47	6.0	87	78	21	73
8	175	29	5.7	81	63	11	83
9	200	34	9.2	73	72	24	67
Organic bay							
2	50	42	4.5	89	89	31	65
14	50	38	2.4	94	85	6	93
3	75	42	3.8	91	95	18	81
13	75	37	3.5	91	73	7	90
4	100	40	4.2	90	82	12	85
5	125	46	7.3	84	82	15	82
6	125	46	6.9	85	78	9	88
10	150	39	5.3	86	72	13	82
11	175	41	6.4	84	88	18	80
12	200	44	8.3	81	85	24	72

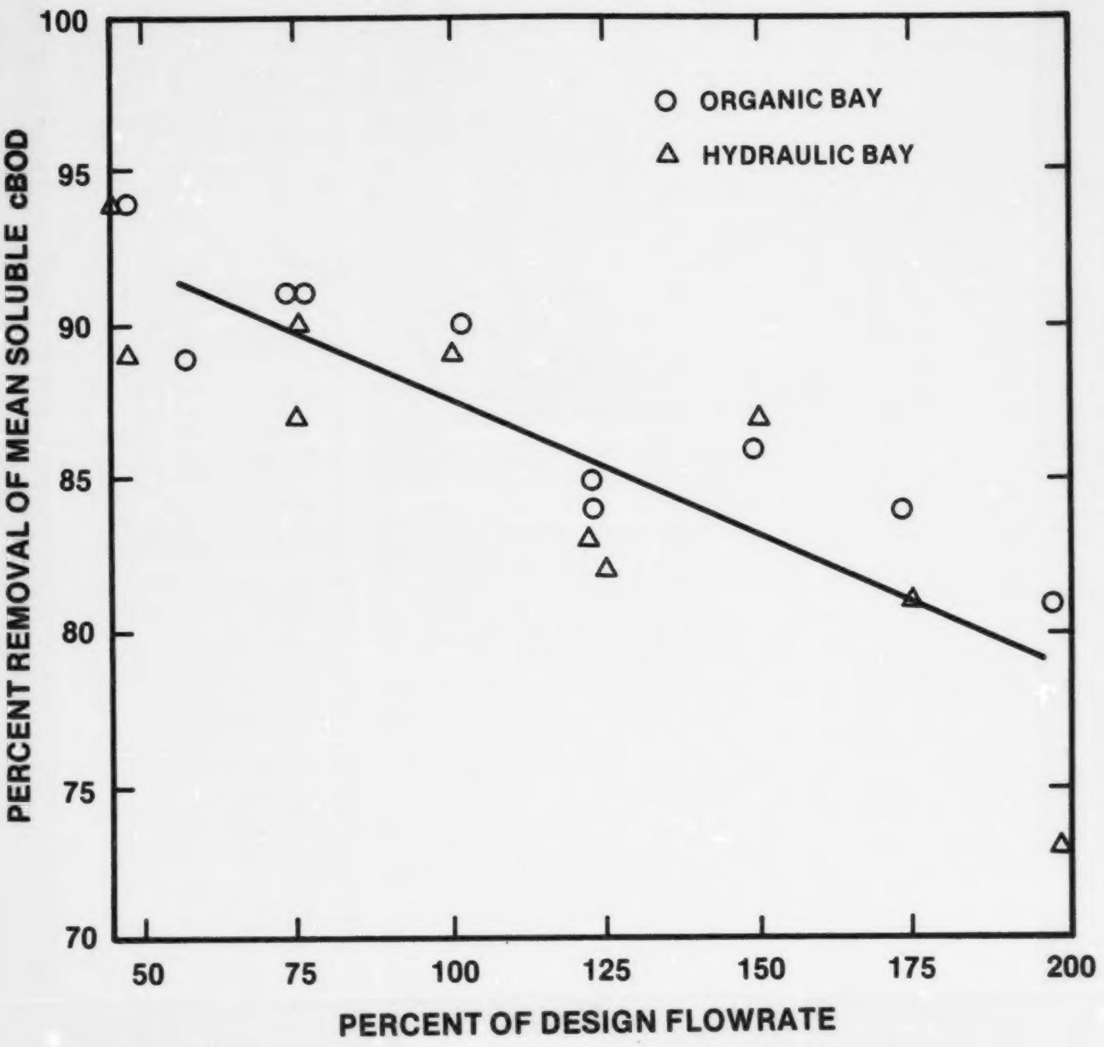

Figure 9. Variation in the removal of mean soluble cBOD with wastewater flowrate for the hydraulic and organic bay experiments.

TABLE 23. COMPARISON OF MEAN SOLUBLE cBOD REMOVAL IN THE HYDRAULIC AND ORGANIC BAY EXPERIMENTS AFTER 800,000 ft^2 OF TREATMENT

Percent of design flowrate	Percent removal of total cBOD	
	Hydraulic bay	Organic bay
50[a]	92[b,c]	92[b]
75[a]	89[b,c]	91[b]
100[a]	89[c]	90
125[a]	83[b,c]	84[b]
150	87	86
175	81	84
200	73	81

[a] side-by-side evaluation

[b] average of two replicate experiments

[c] average after 700,000 and 800,000 square feet of treatment

Variability of Effluent Quality with Changing Influent Quality

The concentration of soluble cBOD entering the Columbus RBC research plant varied from experiment to experiment, and from day-to-day within a particular experiment in response to changing municipal wastewater characteristics. Figures 10 and 11 give the reader insight into the type of variability that occurred in the influent to the hydraulic and organic bays during the course of experiments. Also evident in these figures is the ability of both RBC treatment bays to maintain a low effluent cBOD concentration in spite of the variability of the influent cBOD concentration. Figures 10 and 11 both depict effluent conditions at the 200% design flow experiments, in which the highest mean effluent cBOD values were recorded. Note especially the near constant effluent quality from the organic bay (Figure 10), despite considerable variability in the influent's quality.

The variability in effluent quality was found to decrease as the level of treatment was increased and as the percent of design flowrate was decreased. Experiments at 50%, 75% and 100% design flowrate showed essentially little to no day-to-day variation in effluent soluble cBOD concentrations, even though the influent cBOD quality varied greatly. This can be seen in Figure 12 which shows influent and effluent values for both treatment bays in Experiment 4 (100% design flow).

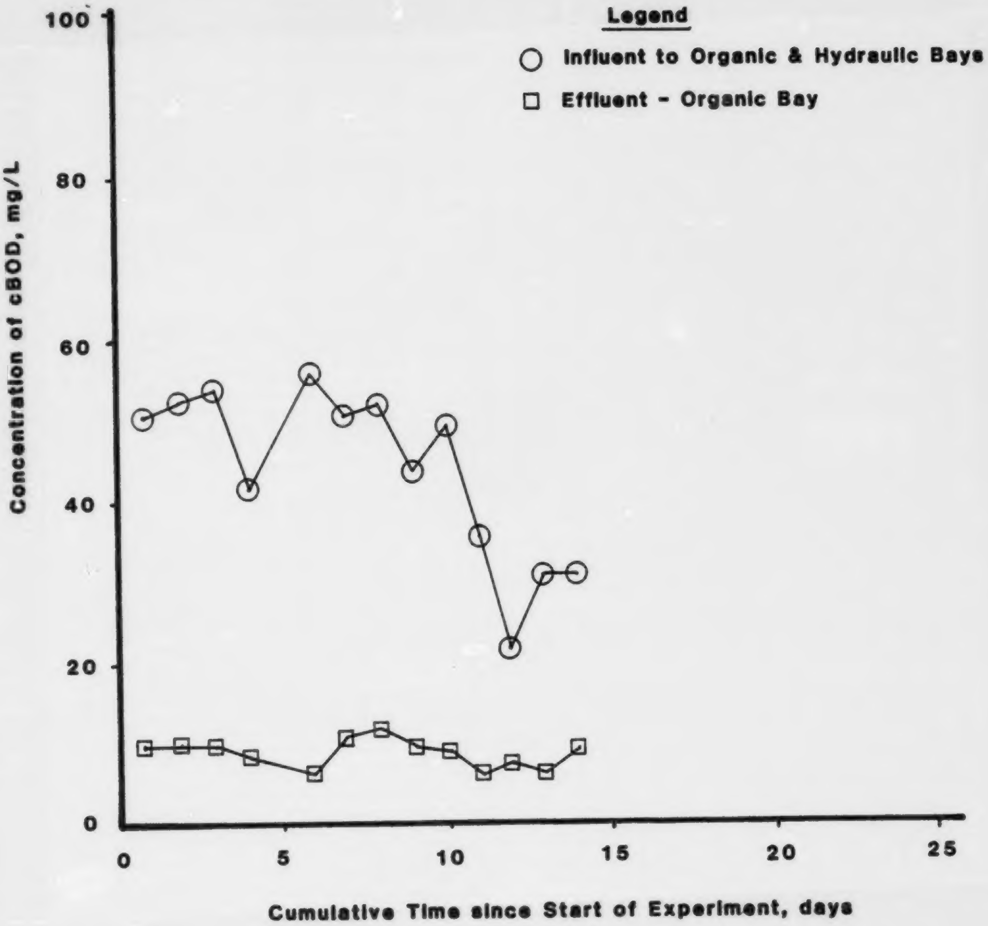

Figure 10. Daily soluble cBOD concentration versus cumulative days of treatment for Experiment 12 in organic bay (200% of design flowrate).

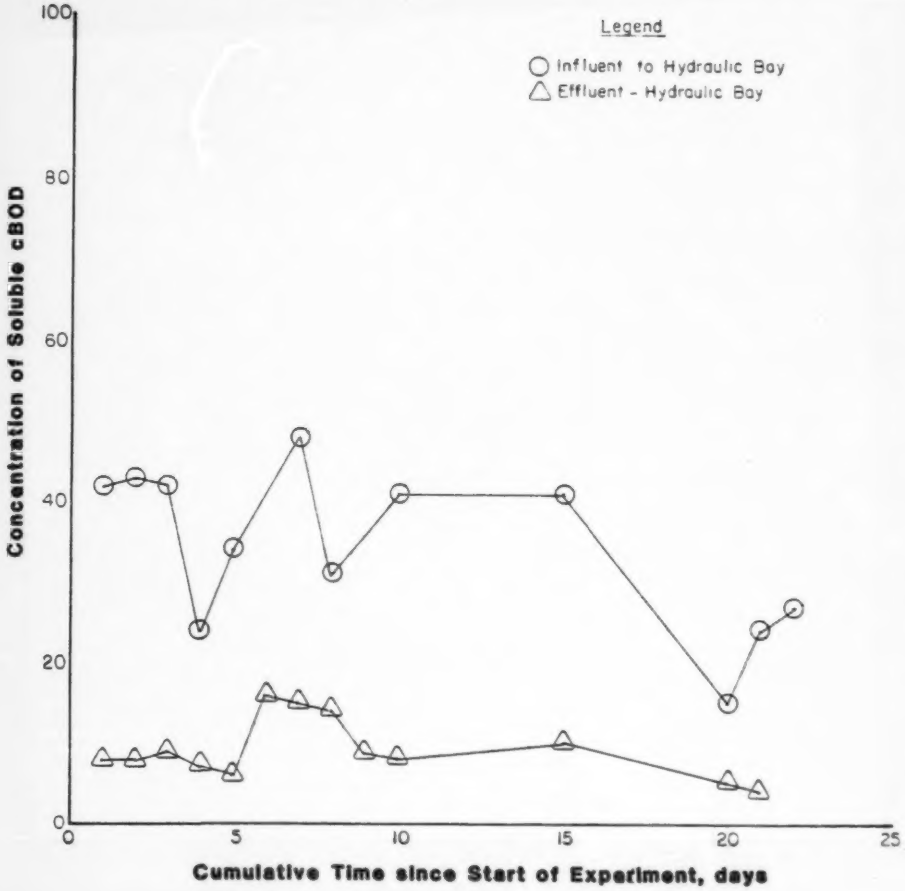

Figure 11. Daily soluble cBOD concentration versus cumulative days of treatment for Experiment 9 in hydraulic bay (200% of design flowrate).

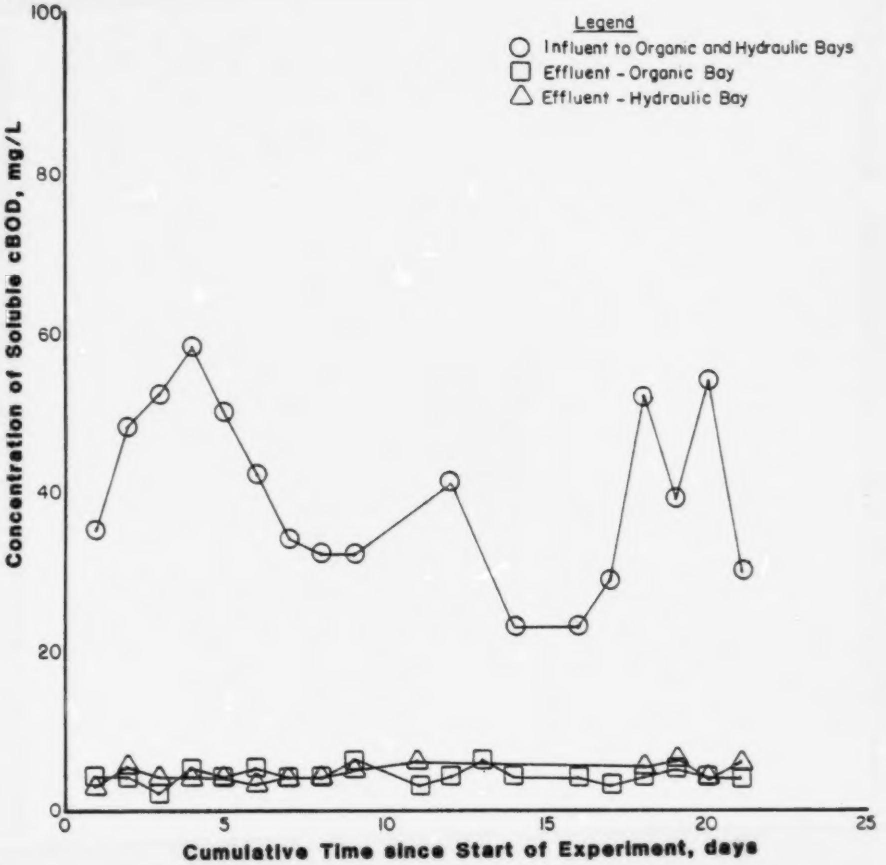

Figure 12. Daily soluble cBOD concentration versus cumulative days of treatment for Experiment 4 in hydraulic and organic bays (100% of design flowrate).

The variability of wastewater quality within the RBC bays during Experiment 5 (125% design flow) is shown in Figure 13. In this figure, daily soluble cBOD values are shown for this 20-day experiment. cBOD concentrations are given for the influent, after 400,000 ft^2 of treatment, and after entire treatment and pilot sedimentation. As shown in Figure 13, the variability of the wastewater's quality after only 400,000 ft^2 of treatment was considerably less than the variability in the influent wastewater. Little to no variability appears in the effluent quality with soluble cBOD levels consistently maintained in the 5-10 mg/L range. In summary, both the organic and hydraulic treatment bays demonstrated an ability to consistently maintain a low soluble cBOD concentration with little or no variability thereto.

Mean Soluble cBOD Concentration versus Stage of Treatment

Mean soluble cBOD concentration versus stage of treatment for the hydraulic and organic bays are listed in Tables 24 and 25, respectively. Figure 14 and 15 graphically depict this same information. It is evident that the rate of removal of soluble cBOD decreased with increased level (stage) of treatment, indicating that the rate of cBOD removal was dependent on the cBOD concentration remaining in solution. It is also evident from Figure 14 that increasing the flowrate to the hydraulic bay resulted in higher cBOD concentrations penetrating further into this treatment bay.

Mean soluble cBOD concentrations measured at various stages of treatment in the organic bay are shown in Figure 15. A significant reduction in the concentration of cBOD was found during the first stage of treatment, which contained 400,000 ft^2 of surface area. With the exception of the 175 and 200% design flowrate experiments, nearly all of the cBOD removed in the organic bay took place by the completion of stage 2 (after a total of 600,000 ft^2 of treatment). Just as was found in the hydraulic bay, the level of cBOD penetrating the organic bay increased with increased flowrate.

Soluble cBOD versus Retention Time Relationship

The concentration of soluble cBOD remaining to be removed during RBC treatment was observed to be dependent upon the cumulative fluid (wastewater) retention time in either the hydraulic or organic bays. Figure 16 is a plot of the mean soluble cBOD concentration for various stages of treatment in the hydraulic bay. In this figure the stage of treatment was converted to a fluid retention time based on the known flowrate applied and the volume of the RBC reactors used at the Columbus wastewater treatment plant. In short, Figure 16 is a plot of all of the cBOD data for the hydraulic bay, which is listed in Table 24, after first converting the stage of treatment to an estimated fluid retention time as described above.

The relationship shown in Figure 16 indicates that the concentration of soluble cBOD remaining to be removed in the hydraulic bay is highly dependent upon the fluid's retention time up to about two hours, beyond which little additional removal is accomplished. Figure 16 also shows that much of the soluble cBOD removed in the hydraulic bay takes place within the first hour of treatment, leaving a residual soluble cBOD concentration of

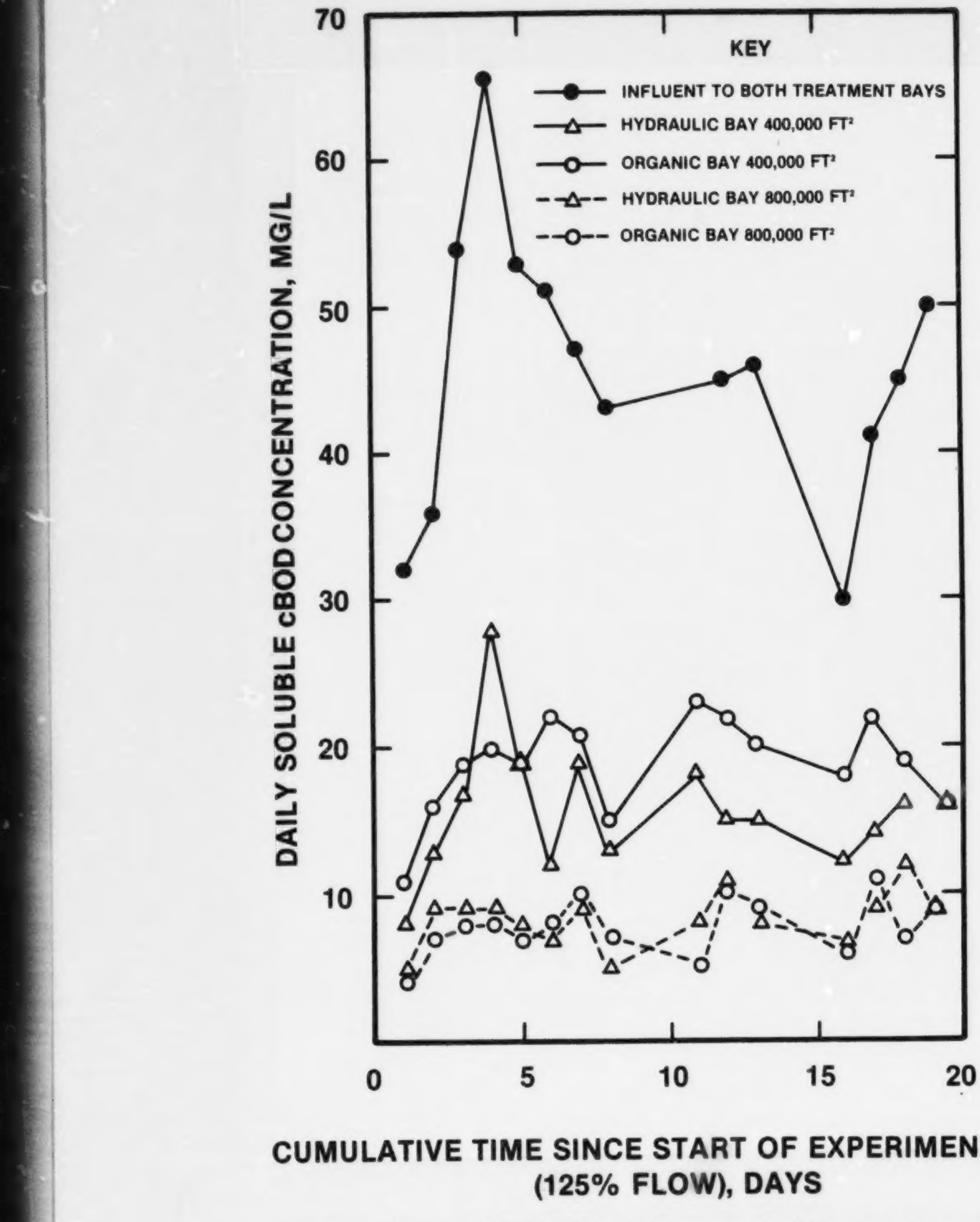

Figure 13. Daily soluble cBOD concentration versus cumulative days of the experiment for Experiment 5 (125% of design flow).

TABLE 24. MEAN SOLUBLE cBOD AND COD CONCENTRATIONS FOR HYDRAULIC BAY EXPERIMENTS

Experiment	2	3	4	5	6	7	8	9	13	14
Percent design flow	50	75	100	125	125	150	175	200	75	50
Stage of treatment				Mean soluble cBOD mg/L						
I	42	42	40	46	46	47	29	34	37	38
1	38	39	38	44	30	33	22	25	18	11
2	19	27	27	31	24	28	20	23	14	6.3
3	11	18	19	25	21	22	16	19	6.8	3.6
4	6.6	13	14	21	15	18	13	18	4.5	3.1
5	-	9	9	16	-	-	-	-	-	-
6	4.9	-	-	-	10	12	9.3	12	5.0	3.2
7	4.4	6.1	5.6	9.6	9.1	8.5	7.2	11	2.9	2.5
E	4.2	5.6	4.5	8.3	7.9	6.0	5.7	9.2	3.5	2.2
				Mean soluble COD, mg/L						
I	108	115	106	116	112	99	86	102	96	117
1	103	115	108	115	94	84	75	96	67	60
2	74	91	86	92	75	80	68	90	58	52
3	56	72	69	81	70	62	60	83	50	44
4	47	59	57	69	63	58	55	80	43	37
5	-	55	51	59	-	-	-	-	-	-
6	38	-	-	-	47	50	47	62	45	37
7	36	51	45	45	40	46	47	66	37	36
E	34	52	41	44	46	46	35	52	36	30

TABLE 25. MEAN SOLUBLE cBOD AND SOLUBLE COD CONCENTRATIONS FOR ORGANIC BAY EXPERIMENTS

Experiment	2	3	4	5	6	10	11	12	12A[a]	13	14	14A[a]
Percent design flow	50	75	100	125	125	150	175	200	75	75	50	200
Stage of treatment						Soluble cBOD mg/L						
I	42	42	40	46	46	39	41	44	26	37	38	42
1	12	11	12	19	19	16	20	25	-	9.2	4.3	-
2	6.7	5.4	6.0	9.8	10	9.1	12	14	-	4.8	2.8	-
3	5.3	4.9	4.9	8.7	8.7	7.2	9.5	13	-	4.2	2.2	-
E	4.5	3.8	4.2	7.3	6.9	5.3	6.4	8.3	-	3.5	2.4	-
						Soluble COD, mg/L						
I	108	115	106	116	112	125	133	136	96	96	117	88
1	57	60	54	63	64	77	98	84	-	58	48	-
2	40	49	40	49	47	57	69	69	-	43	36	-
3	40	47	35	38	41	56	62	70	-	40	34	-
E	41	39	35	42	40	51	54	56	-	36	32	-

[a] Mean cBOD and COD concentrations were calculated for influent only in this experiment due to its experimental design

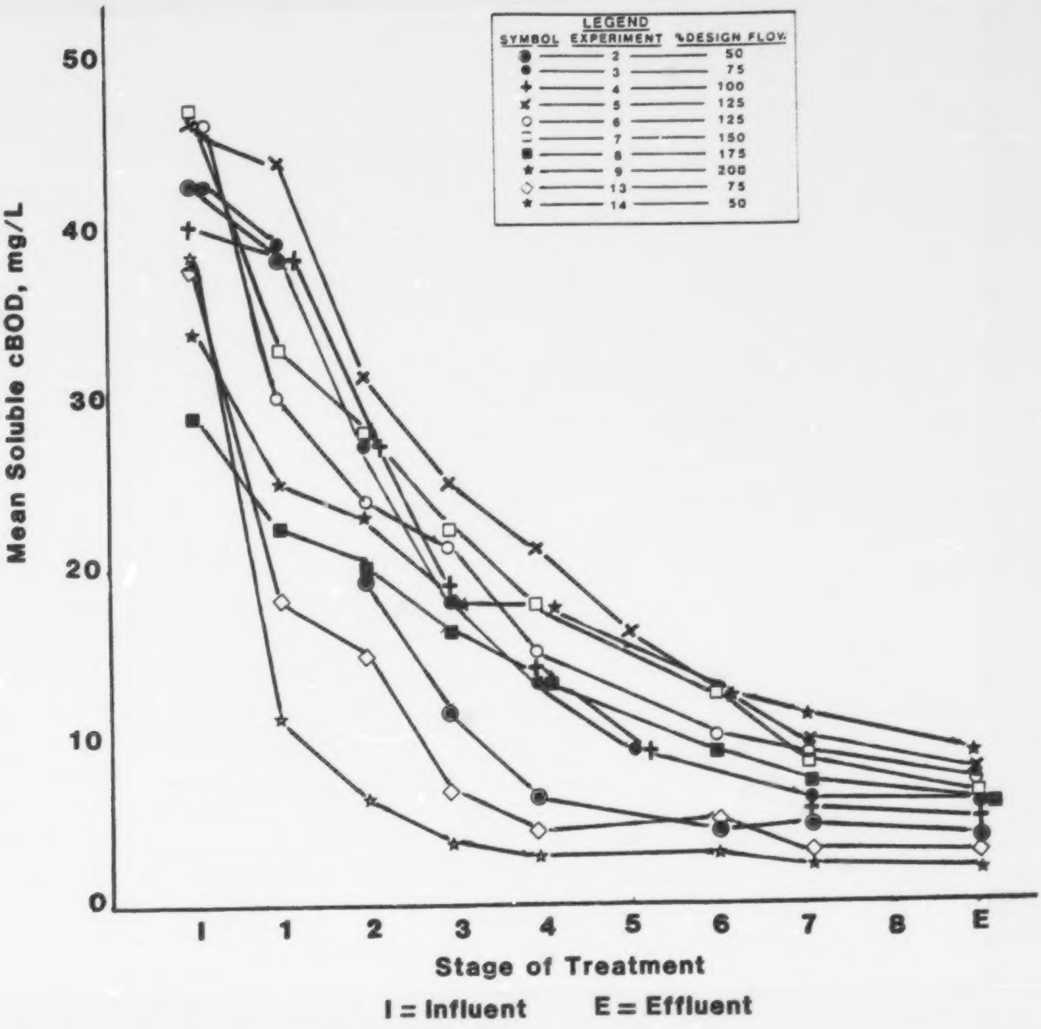

Figure 14. Mean soluble cBOD concentrations versus stage of treatment for hydraulic bay experiments.

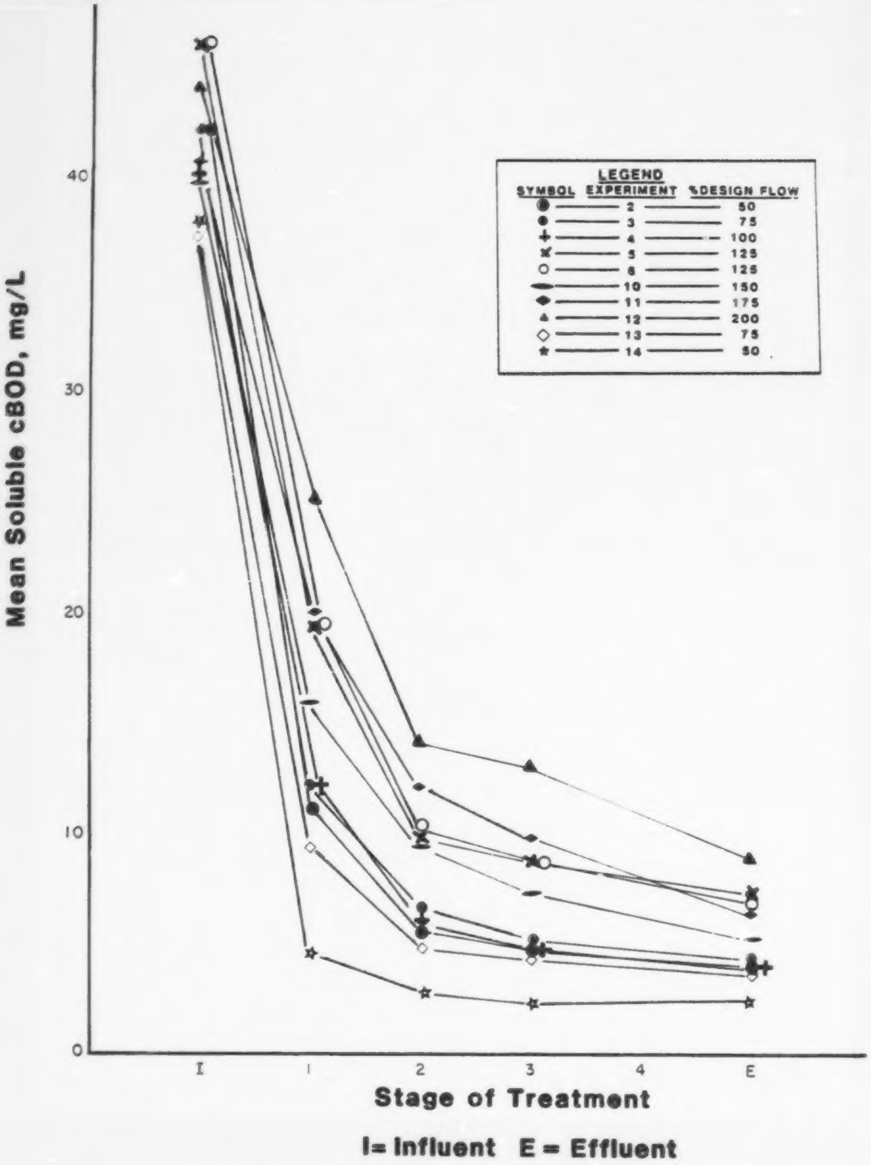

Figure 15. Mean soluble cBOD concentrations versus stage of treatment for organic bay experiments.

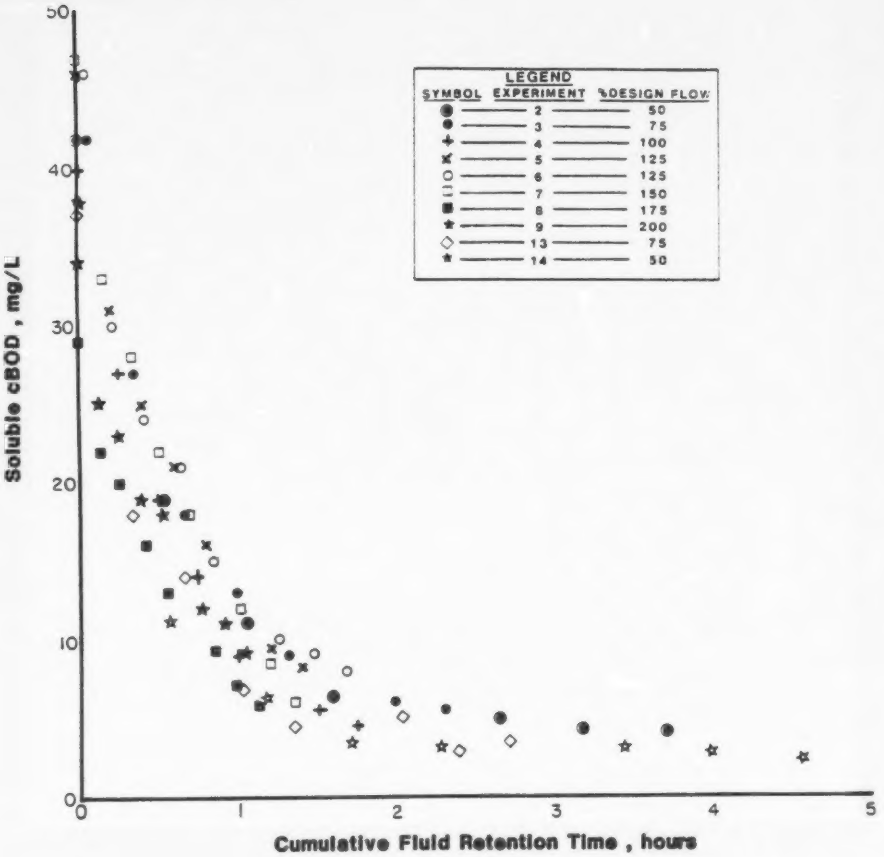

Figure 16. Soluble cBOD concentration versus cumulative fluid retention time for hydraulic bay experiments.

5-10 mg/L. These observations show that RBC treatment is a "high rate" process that achieves low effluent cBOD concentrations in a short fluid retention time.

Figure 17 is the resulting mean soluble cBOD versus fluid retention time relationship for the organic bay data reported in Table 25. Similar trends and observations just made for the hydraulic bay's data are applicable for the organic bay. In Figure 18 the soluble cBOD versus retention time data are plotted for both the hydraulic and organic bay experiments. The data for both bays seem to overlap one another, except for retention times less than one hour. At fluid retention times less than one hour, the organic bay seems to have a slightly higher soluble cBOD concentration remaining to be removed. The reason for this occurrence is not specifically known but is thought to have resulted from the increased level of staging in the hydraulic bay, in comparison to that existing in the organic bay, as would be expected for a non-zero order reaction expression.

Additional Comparisons of Soluble cBOD Removal

A number of other evaluations were attempted to evaluate if the removal of soluble cBOD in the hydraulic bay at 400,000 and 600,000 ft^2 of treatment exceeded that measured in the organic flow configuration. First, all of the experiments completed on a side-by-side basis were reviewed and soluble cBOD concentrations were plotted versus fluid retention time for both treatment bays. Figures 19 and 20 exemplify the results obtained. Some of the plots showed a strong indication that higher levels of mean soluble cBOD remaining to be removed were present in the organic bay (Figure 19), whereas others showed little or no difference (Figure 20), in comparison to the hydraulic bay. In all cases, however the first-stage, mean soluble cBOD concentration in the organic bay was substantially higher than the mean soluble cBOD concentration in the hydraulic bay at a similar retention time. Table 26 is a comparison of these cBOD values for all of the side-by-side experiments. Higher levels of mean soluble cBOD are clearly evident in the organic bay, in comparison to data for the hydraulic bay.

The difference in soluble cBOD concentration between the hydraulic and organic treatment bays was further evaluated by comparing the daily soluble cBOD values, again for hydraulic and organic bay experiments completed on a side-by-side basis. Figures 21 through 23 compare the daily soluble cBOD concentrations for the 400,000 ft^2, 600,000 ft^2, and 700,000 ft^2 level level of treatment. The straight lines appearing in Figures 21-23 were forced through the origin and slopes were calculated with the equation:

$$\text{Slope} = \frac{\Sigma xy}{\Sigma x^2}$$

where x = daily soluble cBOD concentration in the hydraulic bay
y = daily soluble cBOD concentration in the organic bay

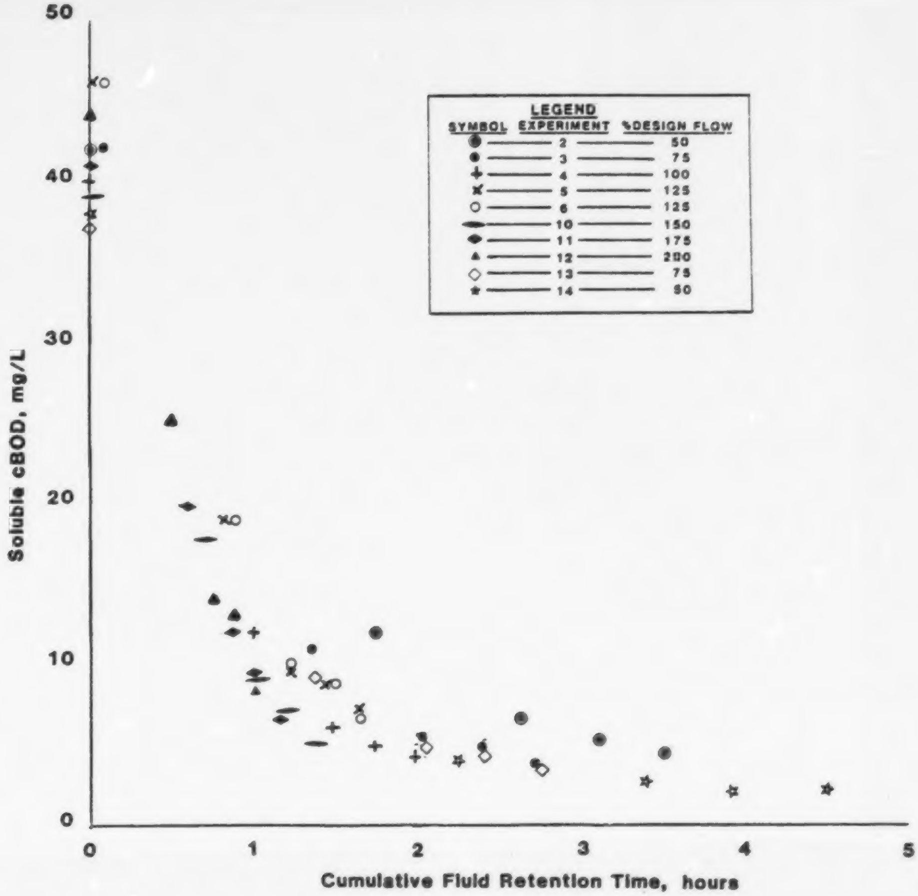

Figure 17. Soluble cBOD concentration versus cumulative fluid retention time for organic bay experiments.

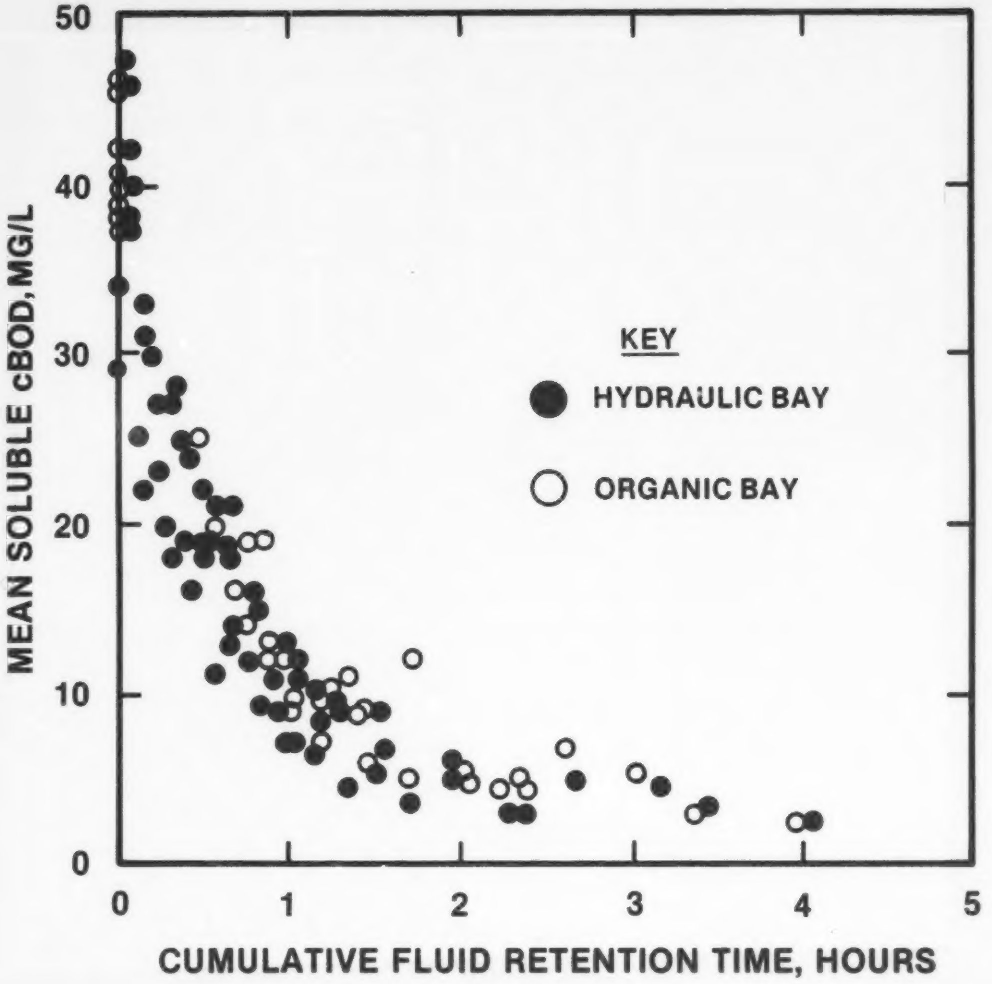

Figure 18. Comparison of mean soluble cBOD concentration versus cumulative wastewater retention time for the hydraulic and organic bay experiments.

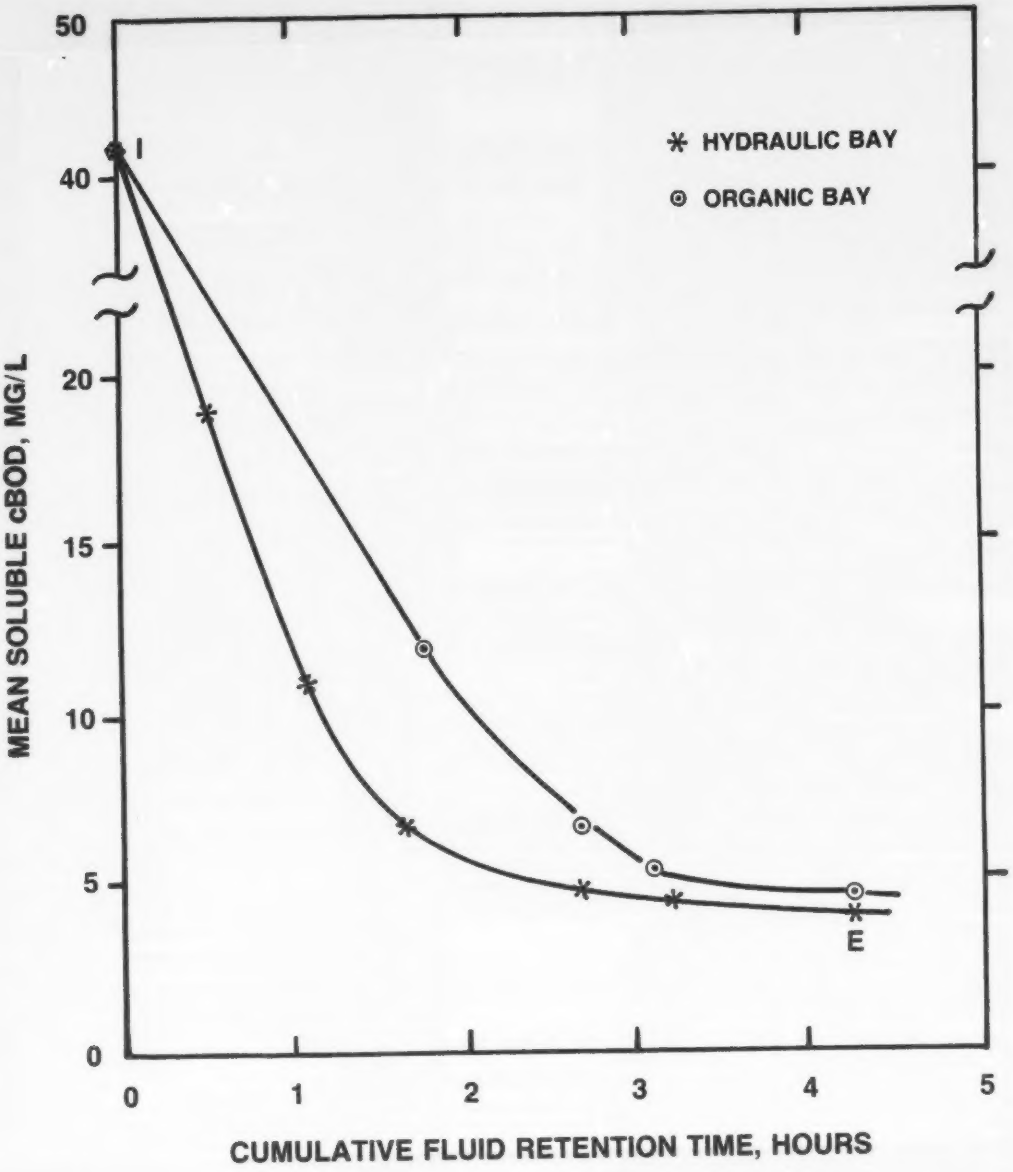

Figure 19. Comparison of mean soluble cBOD concentration versus stage of treatment in hydraulic and organic bays for Experiment 2 (50% design flow).

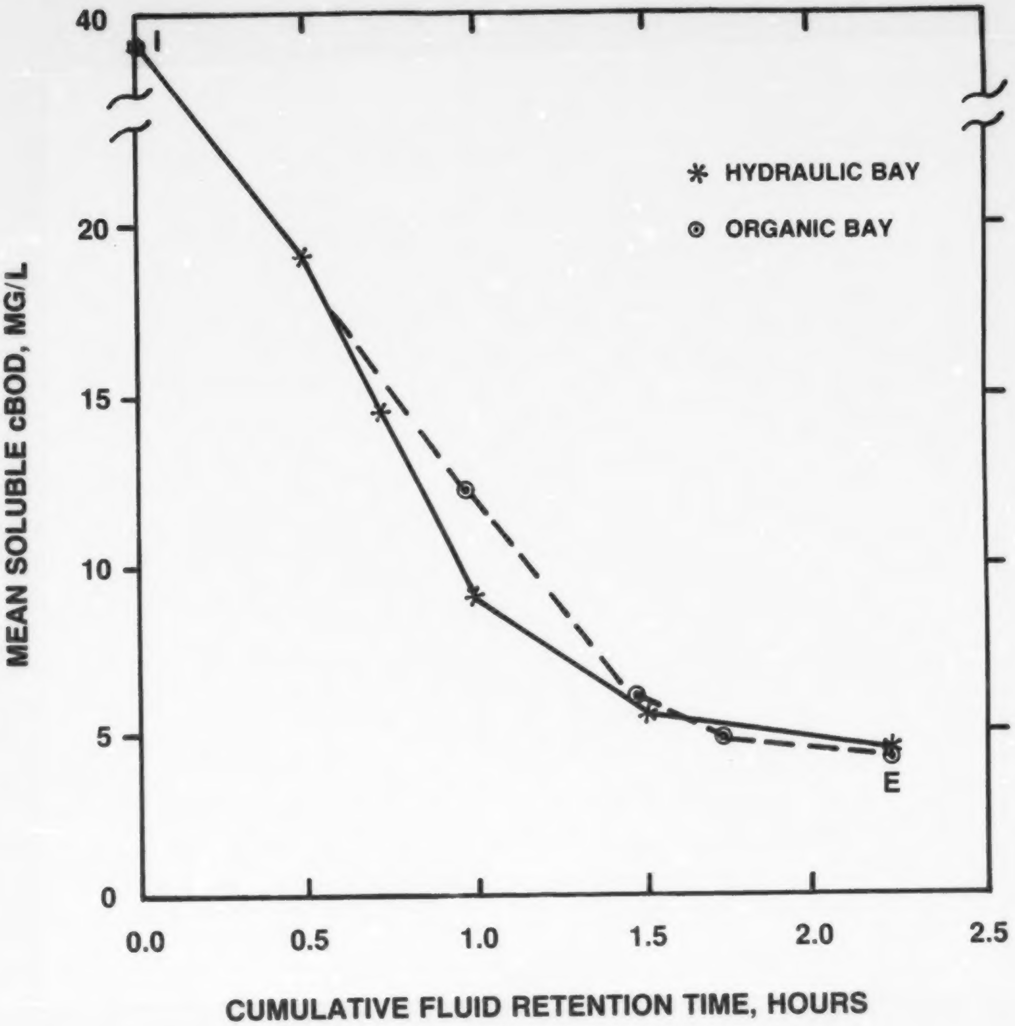

Figure 20. Comparison of mean soluble cBOD concentration versus stage of treatment in hydraulic and organic bays for Experiment 4 (100% design flow).

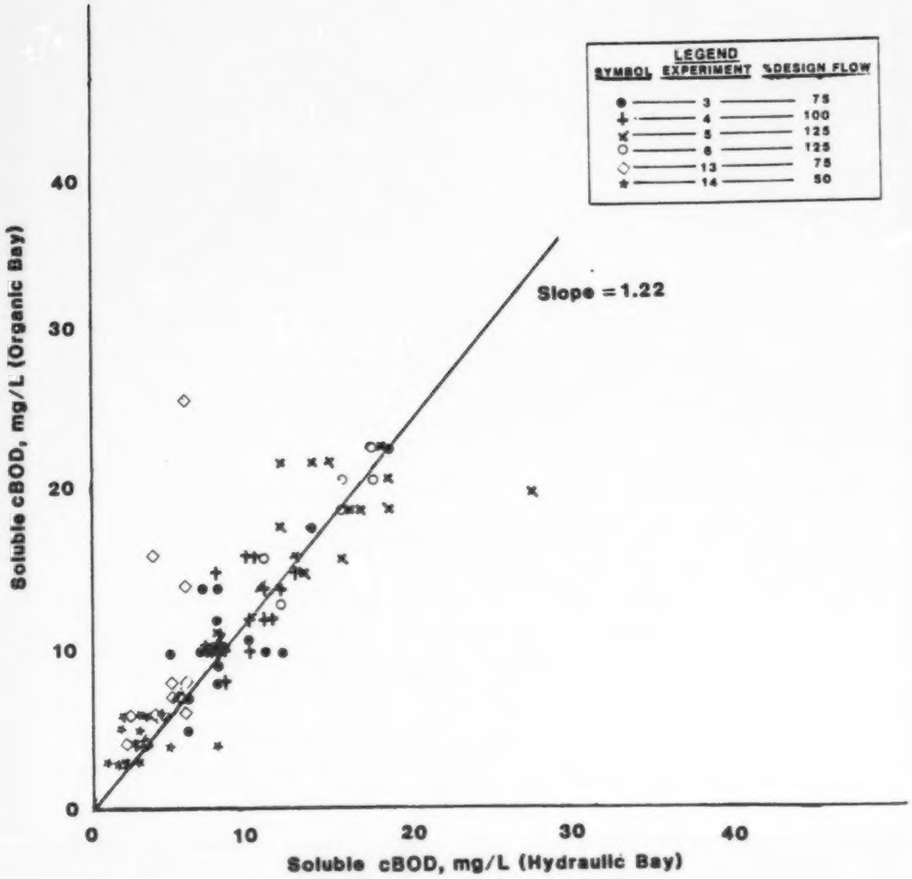

Figure 21. Daily soluble cBOD concentration for organic bay versus hyraulic bay after 400,000 ft^2 of treatment.

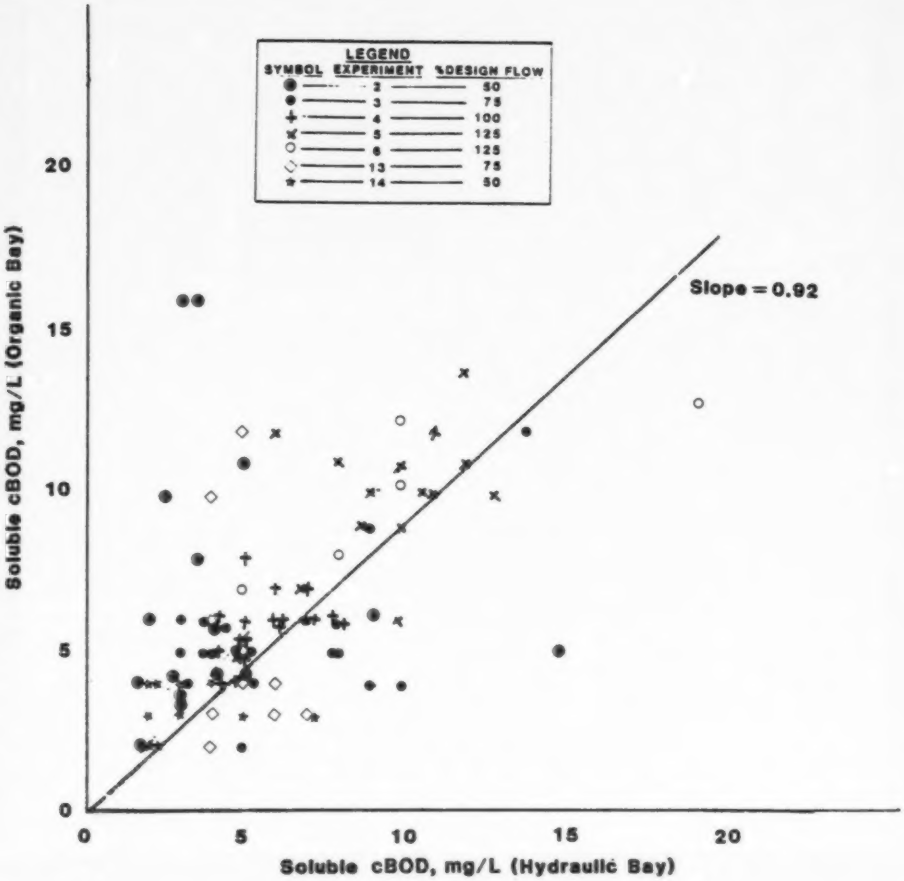

Figure 22. Daily soluble cBOD concentration for organic bay versus hyraulic bay after 600,000 ft^2 of treatment.

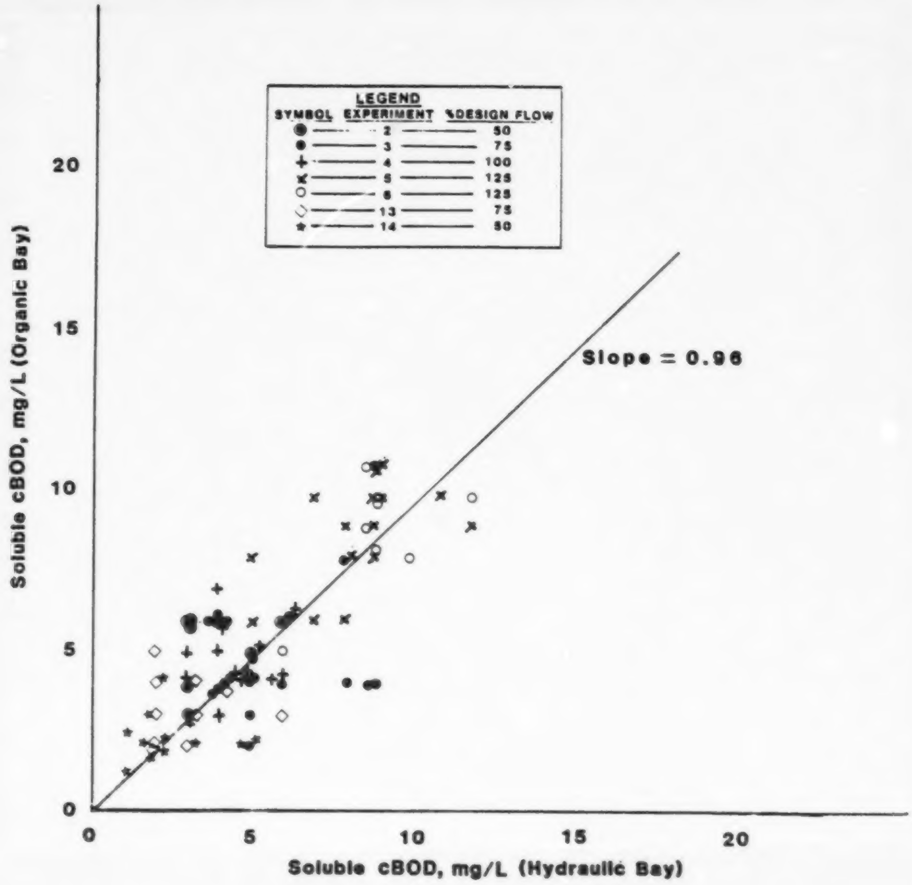

Figure 23. Daily soluble cBOD concentration for organic bay versus hyraulic bay after 700,000 ft^2 of treatment.

TABLE 26. COMPARISON OF MEAN SOLUBLE cBOD FOR THE HYDRAULIC AND ORGANIC BAYS AT 400,000 ft^2 OF TREATMENT[a]

Experiment number	Percent of design flowrate	Soluble cBOD , mg/L	
		Hydraulic bay	Organic bay
2	50	6.6	12
14	50	3.1	4.3
3	75	9	11
13	75	4.5	9.2
4	100	9	12
5	125	16	19
6	125	15	19

[a] Based on the same fluid retention time associated with the first stage of treatment in the organic bay.

The slope of the line of best fit through the data sets are as follows:

level of treatment	slope
400,000 ft^2	1.2
600,000 ft^2	0.92
700,000 ft^2	0.96

The slopes of the line for the 600,000 and 700,000 ft^2 of treatment are fairly close to 1.00, suggesting no difference between the organic and hydraulic bays. In contrast, the slope for the 400,000 ft^2 level of treatment was calculated to be 1.22. This value further suggests that the organic bay has higher soluble cBOD values remaining in solution at this level of treatment, in comparison to cBOD values measured in the hydraulic bay.

A paired t-test analysis of the daily soluble cBOD was also completed. The results are shown in Table 27. The statistical data support the hypothesis that there is a difference between the soluble cBOD values measured in the hydraulic and organic bays at the 400,000 ft^2 level of treatment. This observation is supported with a 90% level of certainty for all six side-by-side experiments for which soluble cBOD data were available. A review of these statistical data for the 600,000 and 700,000 ft^2 level of treatment indicates that the organic bay seemed to have the same treatment effectiveness as the hydraulic bay.

TABLE 27. PAIRED T-TEST ANALYSES OF DAILY SOLUBLE cBOD CONCENTRATIONS FOR THE HYDRAULIC AND ORGANIC BAYS

Experiment	Percent of design flow	Tail area probability for cBOD data at selected levels of treatment		
		400,000 ft^2	600,000 ft^2	700,000 ft^2
2[a]	50	--	0.08[b]	0.20[b]
14	50	0.087[b]	0.49[b]	0.48[c]
3[a]	75	0.004[b]	0.20[c]	0.15[c]
13	75	0.055[b]	0.74[c]	0.58[b]
4[a]	100	0.093[b]	0.71[b]	0.73[b]
5[a]	125	0.0028[b]	0.75[b]	0.39[b]
6	125	0.014[b]	0.80[c]	0.57[c]

[a] Stage 1 in the hydraulic bay was inoperable during this experiment

[b] Mean concentration was greater in the organic bay

[c] Mean concentration was greater in the hydraulic bay

In summary, the hydraulic treatment bay achieved slightly lower soluble cBOD concentrations after 400,000 ft^2 of treatment, than the organic bay. However, there does not appear to be any difference between the two treatment bays at or above 600,000 ft^2 of treatment.

Influent COD and Organic Loading Conditions

Information about the concentration and mass loading rate of soluble COD in the influent to the hydraulic and organic bay experiments is shown in Table 28. The influent mean soluble COD concentration in hydraulic bay Experiments 7 (150% flow), 8 (175% flow) and 9 (200% flow) were slightly lower than the preceding experiment causing the COD mass loading rate to be lower than expected in these experiments. In contrast, the influent concentration of mean soluble COD in organic bay Experiments 10 (150% flow), 11 (175% flow), and 12 (200% flow) were higher than the preceding experiment causing a slightly higher than expected COD mass loading rate in these experiments. These influent COD conditions to the hydraulic and organic bays are similar but not identical to conditions for soluble cBOD described previously.

Influent soluble COD loading rates, expressed on a lbs COD/day/1,000 ft^2 of media area basis, are listed in Tables 29 and 30. Table 29 is a summary of the influent soluble COD loading rates to the hydraulic and organic bays, based on all stages of treatment. As shown in this table, hydraulic and organic bay experiments completed on a side-by-side basis had comparable COD loading rates, whereas there was considerable difference

TABLE 28. WASTEWATER FLOWRATE AND INFLUENT MEAN SOLUBLE COD CONCENTRATION AND MASS LOADING RATE CONDITIONS FOR THE HYDRAULIC AND ORGANIC BAY EXPERIMENTS

Experiment	Percent of design flow	Flowrate (GPM)	Influent soluble COD: Mean concentration (mg/L)	Influent soluble COD: Mass loading rate (lbs/hr)
		Hydraulic Bay		
2	50	405	108	22
14	50	380	117	22
3	75	652	115	38
13	75	634	96	30
4	100	860	106	46
5	125	1075	116	62
6	125	1046	112	59
7	150	1294	99	64
8	175	1500	86	64
9	200	1720	102	88
		Organic Bay		
2	50	491	108	26
14	50	381	117	22
3	75	634	115	36
13	75	626	96	30
4	100	873	106	46
5	125	1060	116	62
6	125	1056	112	59
10	150	1270	125	79
11	175	1477	133	98
12	200	1695	136	115

TABLE 29. COMPARISON OF SOLUBLE COD MASS LOADING RATE FOR ORGANIC AND HYDRAULIC BAYS FOR ALL STAGES OF TREATMENT

Percent of design flowrate	Mass loading rate, lbs COD/day/1,000 ft^2	
	Hydraulic Bay	Organic Bay
50[a]	0.69[b]	0.72[b]
75[a]	1.1[b]	1.0[b]
100[a]	1.6	1.4
125[a]	1.9[b]	1.8[b]
150	1.9	2.4
175	1.9	2.9
200	2.6	3.4

[a] side-by-side evaluation

[b] average of two replicate experiments

TABLE 30. COMPARISON OF SOLUBLE COD MASS LOADING RATE FOR THE FIRST STAGE OF TREATMENT

Percent of design flowrate	Mass loading rate, lbs COD /day/1,000 ft^2	
	Hydraulic Bay	Organic Bay
50[a]	5.3[b]	1.4[b]
75[a]	8.2[b]	2.0[b]
100[a]	11.1	2.8
125[a]	15[b]	3.6[b]
150	15	4.7
175	16	5.9
200	21	6.9

[a] side-by-side evaluation

[b] average of two replicate experiments

between COD loading rates in the hydraulic and organic bays at the 150%, 175% and 200% design flow experiments.

Table 30 gives a comparison of the soluble COD mass loading rate for the first stage of treatment in both treatment bays. The ability of the organic bay's flow configuration (i.e., 400,000 ft^2 of media area in first stage of treatment) to lower the organic loading rate is clearly evident from this comparison.

Soluble COD Removal

Table 31 lists information about the concentration of mean soluble COD in the influent and effluent to the treatment bays. The percentage of the influent removed by all stages of treatment is also listed in this table. Mean effluent COD concentrations for the various experiments were in the 30-60 mg/L range indicating that a fraction of the soluble COD was "refractory" and not subject to removal by the biological treatment process. The inclusion of this refractory component in the COD measurement causes lower percentage removals for COD, in comparison to values reported earlier for soluble cBOD. The percent removal of soluble COD was in the 50-75% range and appeared to decrease as the flowrate was increased.

A comparison of the percent removal of mean soluble COD in the hydraulic and organic bays is shown in Table 32 and Figure 24. Again, there appears to be a reduction in the percentage of COD removed as the experimental flowrate was increased. Percent COD removal in the organic bay appeared to be slightly better than that accomplished in the hydraulic bay, when compared after all stages of treatment are completed. Caution should be used in this interpretation, however, because the influent COD concentrations to the organic and hydraulic bays during the 150%, 175% and 200% design flow experiments were markedly different. The better COD removal in the 150% and 200% organic bay experiments may have resulted from the increased influent soluble COD concentration, in comparison to influent COD conditions in the hydraulic bay experiments.

The difference in performance between the organic and hydraulic bays is further illustrated in Figure 25 where the concentration of soluble COD removed is plotted as a function of experimental flowrate. The concentration of soluble COD removed in the hydraulic bay decreased as the flowrate was increased. In contrast, the concentration of soluble COD removed in the organic bay experiments was constant or increased slightly as the flowrate was increased. Again, the differences between the hydraulic and organic bays in the removal of soluble COD at the 150%, 175% and 200% flowrates are difficult to properly evaluate because of differing influent conditions.

Variability of Effluent Quality with Changing Influent Quality

The concentration of soluble COD in the influent to the treatment bays varied from day to day. The upper graph in Figure 26 shows daily influent soluble COD concentrations for Experiment 4 (100% design flow condition).

TABLE 31. COMPARISON OF SOLUBLE AND TOTAL COD REMOVALS IN THE HYDRAULIC AND ORGANIC BAY EXPERIMENTS

		Soluble COD					
		Hydraulic bay			Organic bay		
Experiment	Percent design flow	I mg/L	E mg/L	Removed %	I mg/L	E mg/L	Removed %
2	50	108	34	69	108	41	62
14	50	117	30	74	117	32	72
3	75	115	52	63	115	39	66
13	75	96	36	62	96	36	62
4	100	106	41	61	106	35	67
5	125	116	44	62	116	42	64
6	125	112	46	59	112	40	65
7(10)[a]	150	99	46	53	125	51	59
8(11)	175	86	35	60	133	54	59
9	200	102	52	49	136	56	59

[a] parenthesized values are for organic bay

TABLE 32. COMPARISON OF SOLUBLE COD REMOVAL IN THE HYDRAULIC AND ORGANIC BAY EXPERIMENTS AFTER 800,000 ft^2 OF TREATMENT

	Percent COD removal	
Percent of design flowrate	Hydraulic bay	Organic bay
50[a]	72[b,c]	67[b]
75[a]	58[b,c]	64[b]
100[a]	61[c]	67
125[a]	60[b,c]	64[b]
150	53	59
175	60	59
200	49	59

[a] side-by-side evaluation

[b] average of two replicate experiments

[c] average of 700,000 and 800,000 ft^2 of treatment

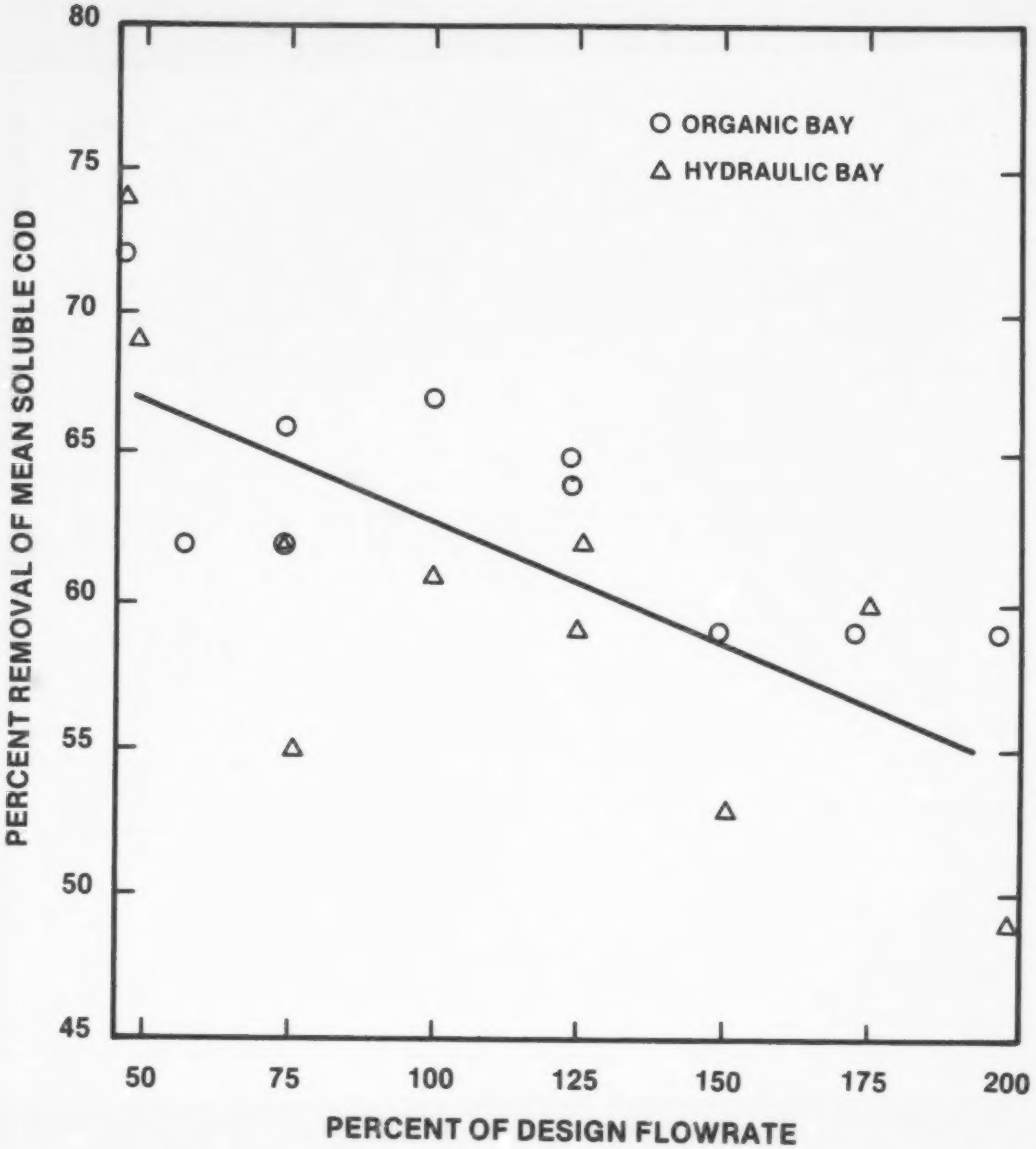

Figure 24. Variation in the removal of mean soluble COD with wastewater flowrate for the hydraulic and organic bay experiments.

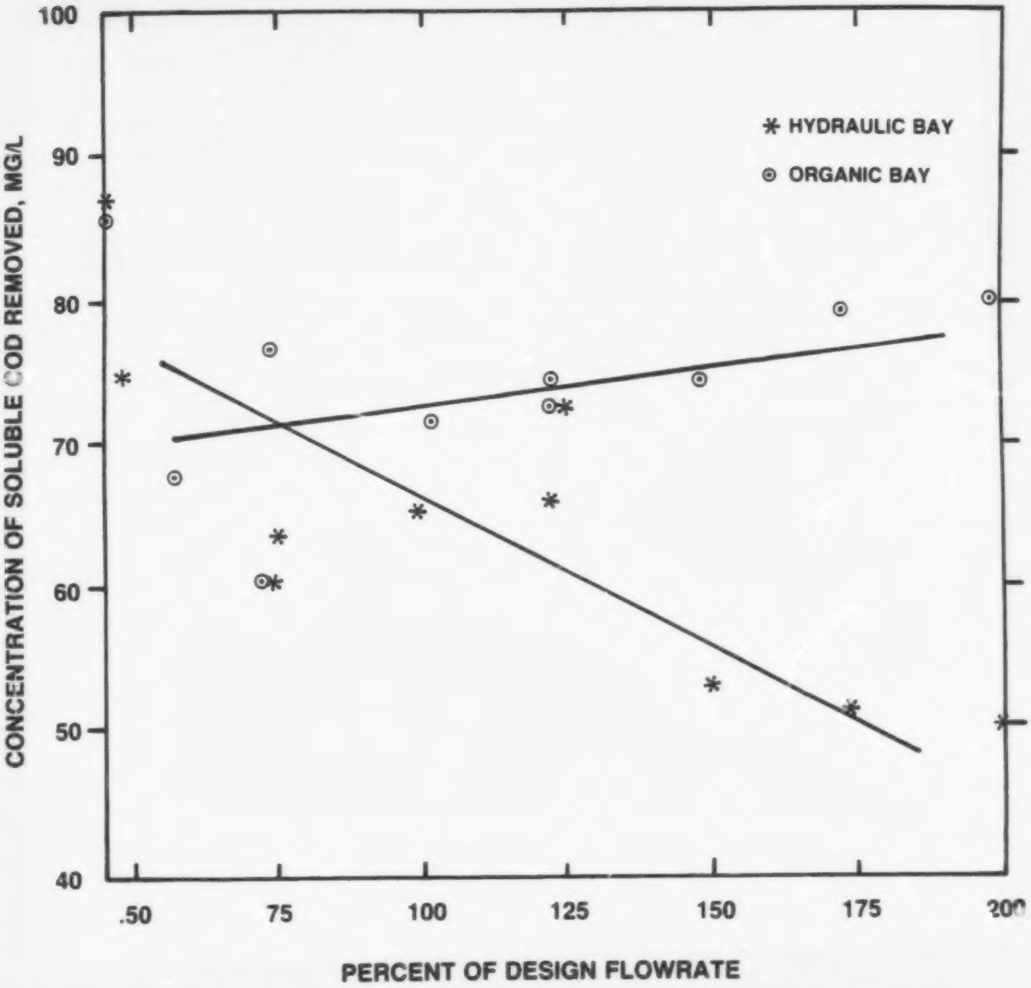

Figure 25. Comparison of soluble COD removed versus wastewater flowrate for the hydraulic and organic bays.

The variation in the influent daily COD concentrations shown for Experiment 4 is typical of conditions that existed in all of the experiments.

The concentration of soluble COD in the effluent from the hydraulic and organic bays in Experiment 4 is shown in Figure 26. Both the hydraulic and organic bay flow configurations were capable of reducing the concentration variability of soluble COD in the influent. This capability of diminishing the daily COD variation in the influent feed was apparent in all experiments completed as part of this investigation.

Mean Soluble COD Concentration versus Stage of Treatment

Tables 24 and 25 list the COD concentration data by stage of treatment for the hydraulic and organic treatment bays, respectively. Graphic illustrations of these data are given in Figures 27 and 28. The concentration profiles for soluble COD are similar to those reported previously for soluble cBOD. Figure 27 shows that most of the removal of soluble COD in the hydraulic bay was accomplished in the first 4 or 5 stages of treatment, with little COD removal thereafter. Similarly, most of the soluble COD removal in the organic bay was accomplished in the first two stages of treatment (Figure 28).

The "refractory" portion of the soluble COD for the Columbus wastewater is also evident in Figures 27 and 28. Approximately, one quarter to one third of the influent soluble COD concentration was refractory in nature. The refractory portion of the soluble COD varied from experiment to experiment but was in the 30-40 mg/L range for most of the experiments.

Soluble COD Versus Retention Time Relationship

The concentration of mean soluble COD remaining to be removed was found to be dependent upon the wastewater's retention time. This relationship is shown in Figure 29 where soluble COD data for both the hydraulic and organic bays are illustrated. The data points shown in Figure 29 comprise all of the mean soluble COD data reported in Tables 24 and 25.

It is apparent from Figure 29 that the removal level of soluble COD is highly dependent upon the wastewater's retention time for the first two hours of treatment. Beyond this time, the rate of removal of soluble COD becomes extremely slow.

Both the hydraulic and organic bays exhibit the same type of soluble COD versus retention time relationship. However, some of the data points for the organic bay plot above the general trend indicated for the hydraulic bay, suggesting that the latter is more effective in the removal of soluble COD. This is especially evident for retention times of less than one hour. The better performance of the hydraulic bay at these low retention times probably resulted from the higher level of staging inherent in the hydraulic bay's flow configuration, in comparison to that present in the organic bay.

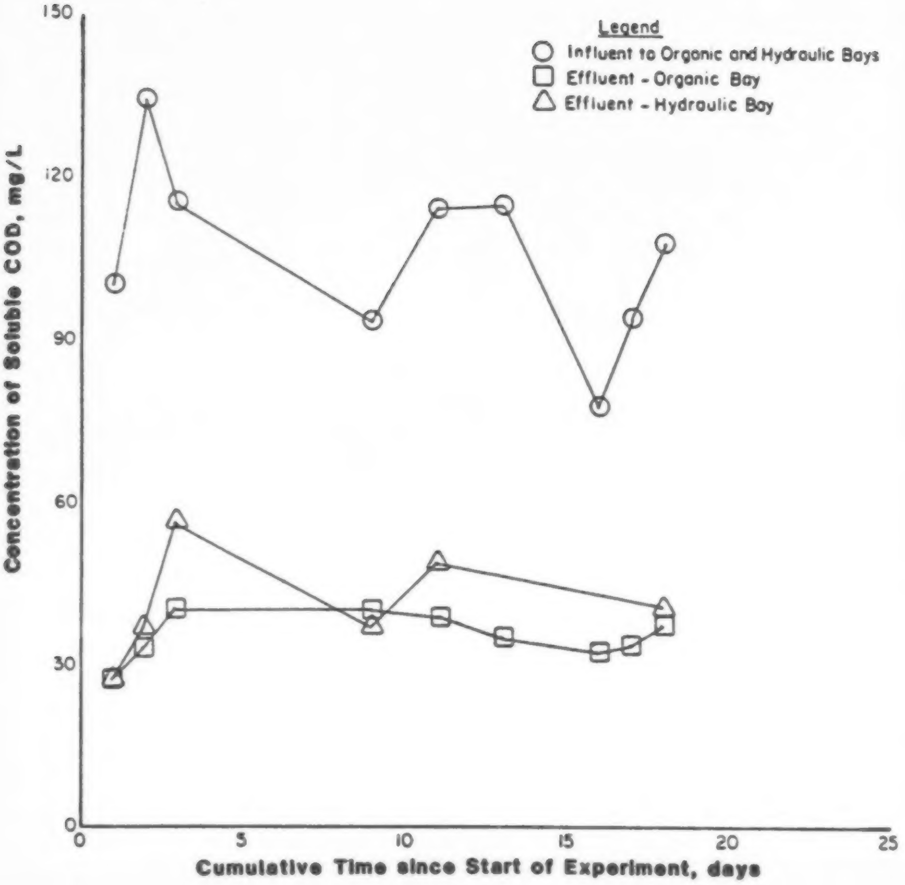

Figure 26. Daily soluble COD concentration versus cumulative days of treatment for Experiment 4 in hydraulic and organic bays (100% of design flowrate).

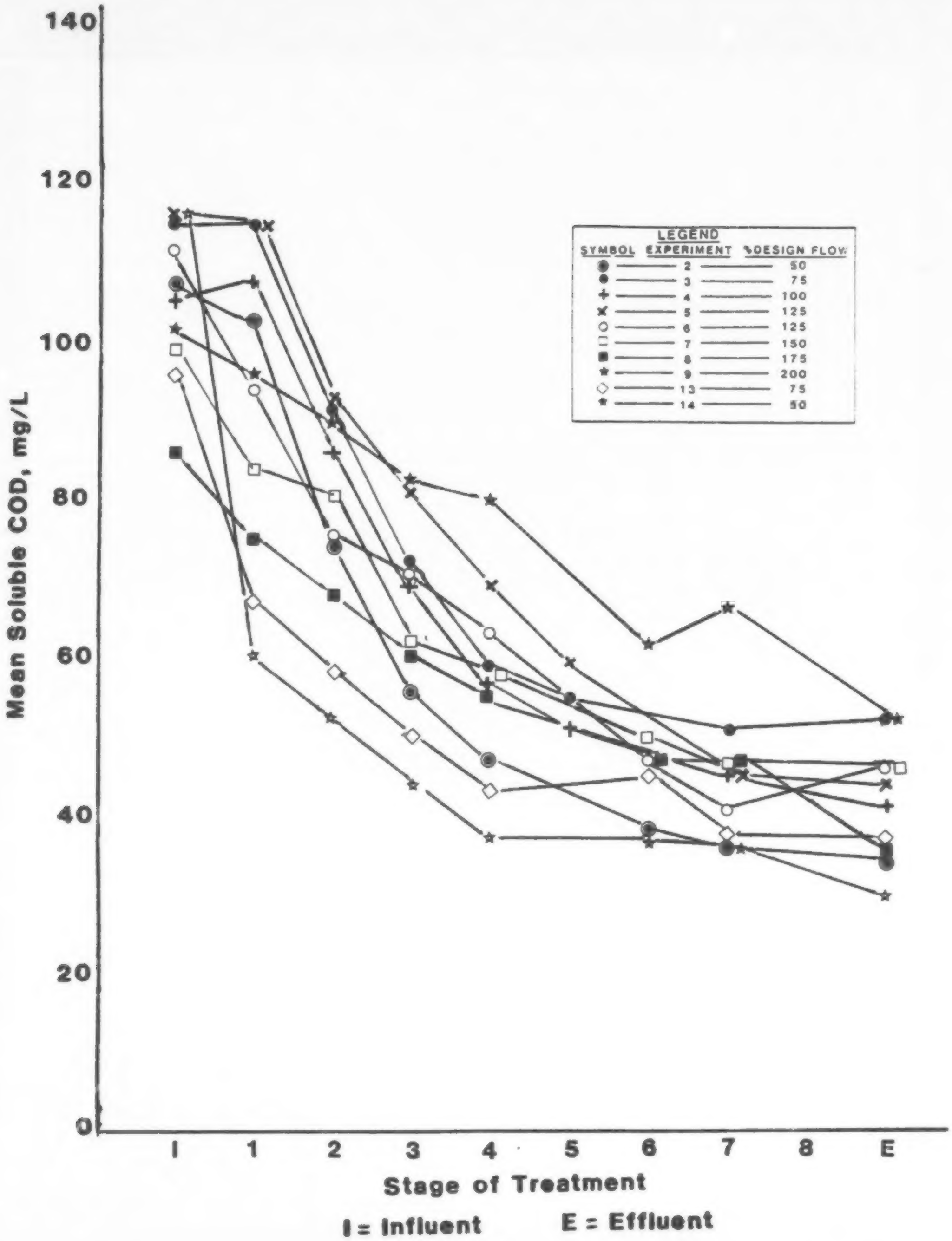

Figure 27. Mean soluble COD concentration versus stage of treatment for hydraulic bay experiments.

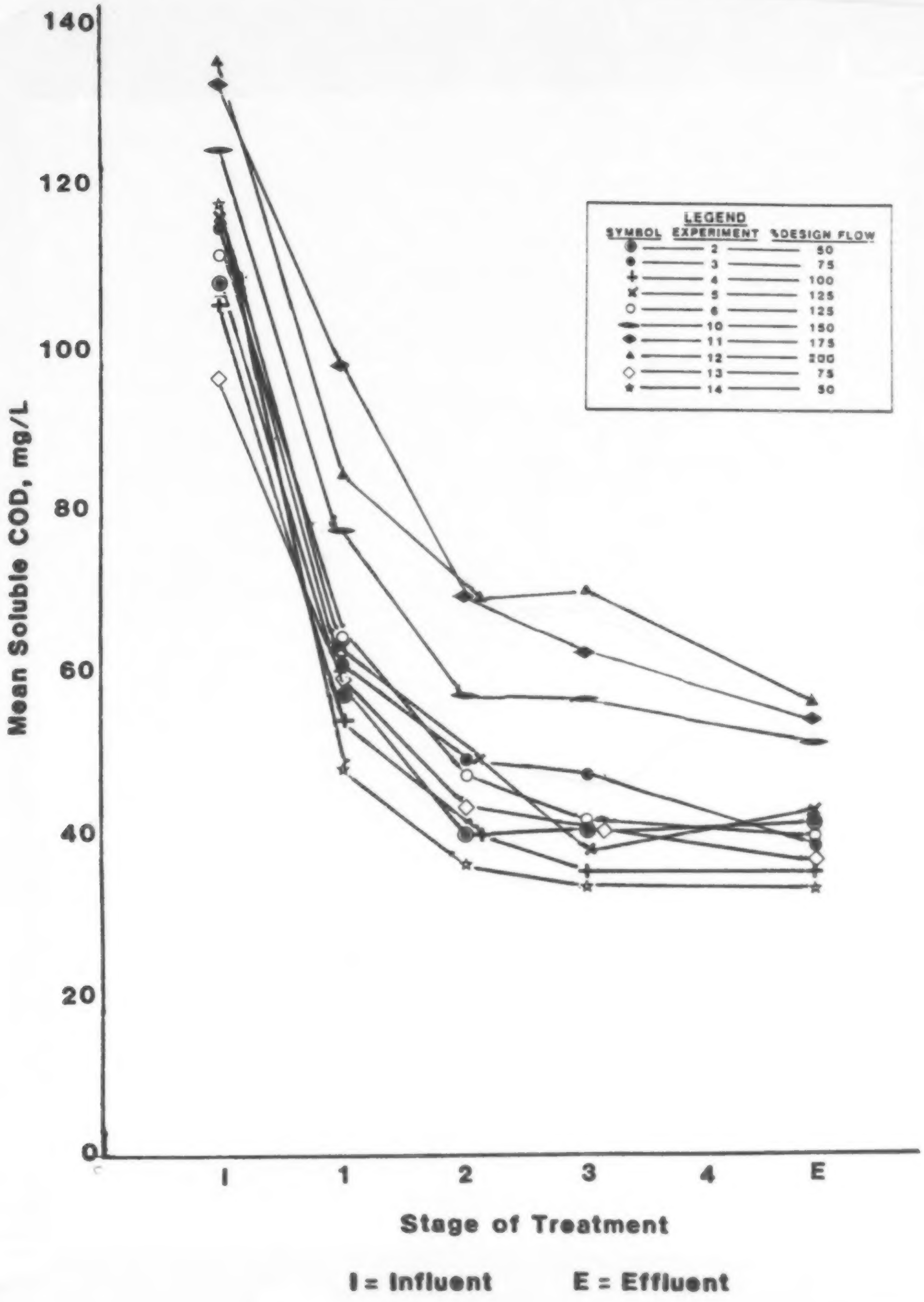

Figure 28. Mean soluble COD concentration versus stage of treatment for organic bay experiments.

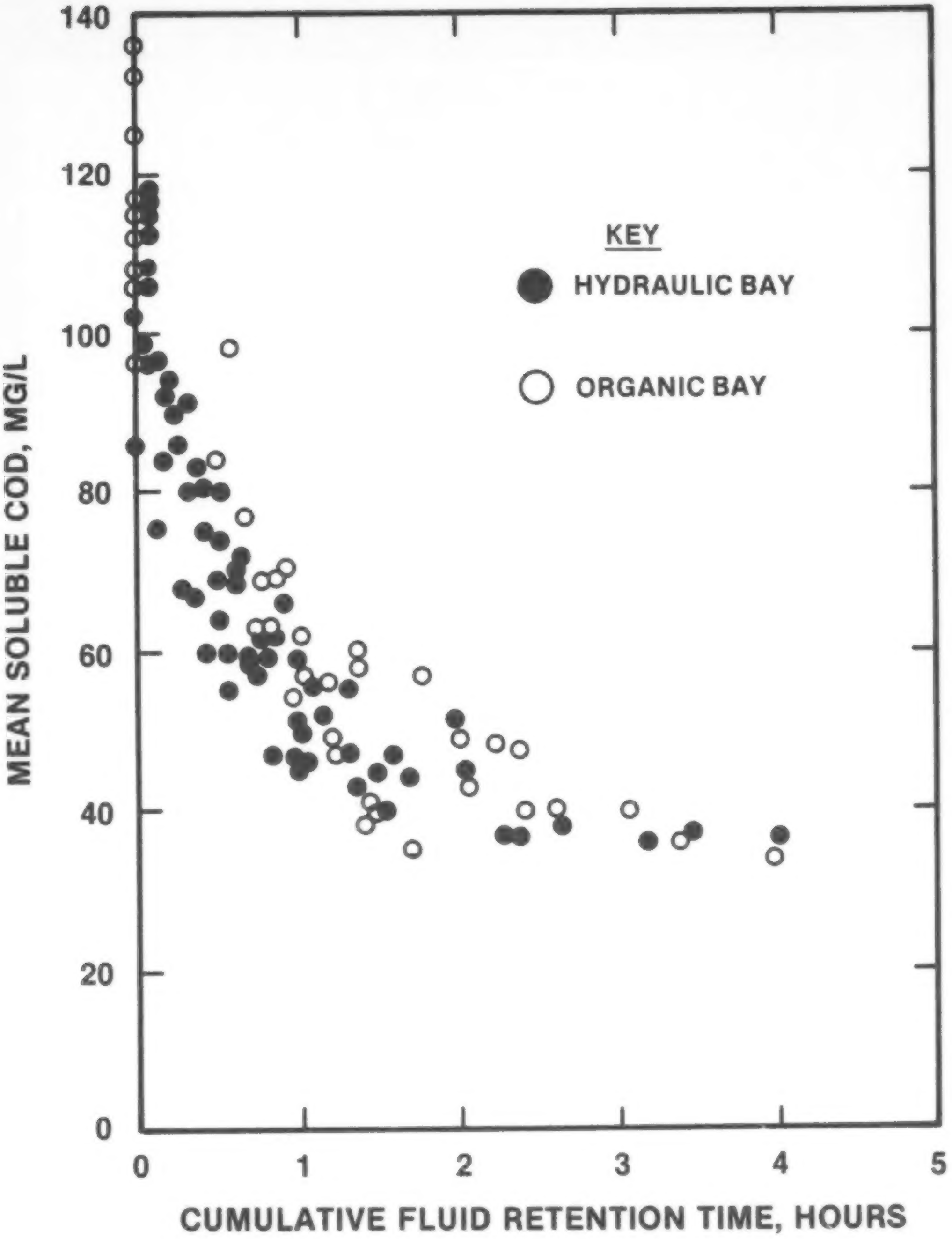

Figure 29. Comparison of mean soluble COD concentration versus cumulative wastewater retention time for the hydraulic and organic bay experiments.

Additional Comparison of Soluble COD Data

The analysis of soluble cBOD data after 400,000 ft^2 of treatment showed that the hydraulic bay's flow configuration was slightly more effective in removing cBOD than the organic bay. A similar trend is apparent for the removal of soluble COD.

Table 33 is a summary of the concentration of mean soluble COD remaining after 400,000 ft^2 of treatment in the side-by-side hydraulic versus organic bay experiments. As evident from Table 33, higher mean soluble COD concentrations were consistently present in the organic bay. This trend was confirmed by a plot of daily soluble COD data for the same side-by-side experiments and at the same level of treatment (Figure 30). Daily soluble COD concentrations tended higher for the organic bay, in comparison to the hydraulic bay. This can be seen in Figure 30 where the majority of the data points fall above a line having a 1.00 slope. If there were no treatment differences between the hydraulic and organic bays, the soluble COD data would have plotted exactly on this line or have a uniform distribution above and below it.

AMMONIA-NITROGEN

The concentration of ammonia-nitrogen at each stage of treatment for the hydraulic bay is presented in Table 34. No ammonia-nitrogen samples were collected during Experiment 3. Influent concentrations ranged from 7.1 mg/L during Experiment 14 to 20.2 mg/L during Experiment 8. Effluent concentrations ranged from 0.0 mg/L during Experiment 13 (75% of design flow) to 17.9 mg/L during Experiment 8 (175% of design flow). The reduction of ammonia-nitrogen concentration decreased with increasing flowrate. At 50% and 75% of design flow, effluent concentrations were essentially zero, while at 175% and 200% of design flow very little decrease in ammonia-nitrogen concentration was observed. Figures 31, 32, and 33 present the concentration of ammonia-nitrogen versus stage for representative experiments at 50%, 100%, and 200% of design flow. At 50% of design flow (Figure 31) the ammonia-nitrogen concentrations were essentially zero by stage 3. Figure 32 shows that at 100% of design flow the ammonia-nitrogen conversion was occurring later in the treatment train and the concentrations remained higher. In contrast only minimal reductions in ammonia-nitrogen concentrations were observed at 200% of design flow. Cumulative percent removal of ammonia-nitrogen concentration varied from 7% at 200% of design flow to 100% at 75% design flow (Table 35). During different days of the same experiment, effluent concentrations and percent removals sometimes differed markedly (Experiments 5 and 8).

The concentration of ammonia-nitrogen for various stages of treatment of the organic bay is presented in Table 36. As in the hydraulic bay, the influent ammonia-nitrogen concentrations varied from 7.1 mg/L in Experiment 14 to 17.4 mg/L in Experiment 4. Generally, the concentration of ammonia-nitrogen decreased through each stage of treatment. The concentration in the effluent ranged from 0.0 mg/L in Experiment 13 to 11.4 mg/L in Experiment 4. Except for day number 21 in Experiment 4, the effluent concentration of ammonia-nitrogen was less than 2 mg/L for all

TABLE 33. COMPARISON OF MEAN SOLUBLE COD CONCENTRATIONS FOR THE HYDRAULIC AND ORGANIC BAYS AT 400,000 ft^2 OF TREATMENT[a]

Experiment number	Percent of design flowrate	Soluble COD, mg/L Hydraulic bay	Soluble COD, mg/L Organic bay
2	50	42	57
14	50	37	48
3	75	55	60
13	75	43	58
4	100	51	54
5	125	59	63
6	125	63	64

[a] Based on the same fluid retention time associated with the first stage of treatment in the organic bay.

experiments operating at or below 100% of design flow. This day also had the highest observed influent concentration at 17.4 mg/L. At flowrates higher than 100% of design flow the effluent concentration of ammonia-nitrogen was always greater than 4 mg/L. Figures 34, 35, and 36 show the concentration of ammonia-nitrogen versus stage of treatment for organic bay experiments at 50%, 100%, and 200% of design flow, respectively. Ammonia-nitrogen concentration was completely reduced after one stage of treatment at 50% of design flow while at 100% of design flow, the removal occurred in later stages and with decreased efficiency. Only slight reductions of ammonia-nitrogen concentrations were observed at 200% of design flow.

In Table 37 the cumulative percent reduction of ammonia-nitrogen concentration is presented for the organic bay. Reduction of ammonia-nitrogen ranged from 21% at 200% of design flow to 100% at 75% of design flow. Below 100% of design flowrate, the ammonia-nitrogen concentration was reduced by 85% while above 125% of design flow the reduction never exceeded 40%.

Figures 37 and 38 present the ammonia-nitrogen concentrations in the organic bay versus the hydraulic bay. At both 400,000 ft^2 and 600,000 ft^2 the hydraulic bay performed better than the organic bay. This is supported by the statistical data presented in Table 38. At 700,000 ft^2

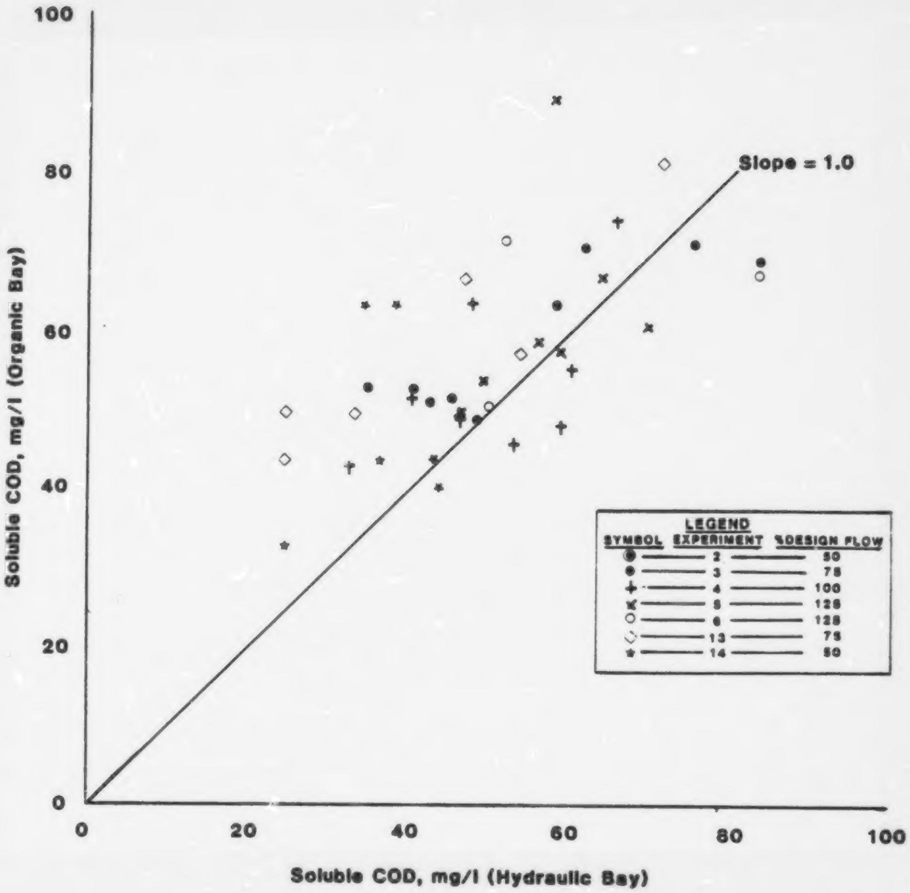

Figure 30. Daily soluble COD concentration for organic bay versus hydraulic bay after 400,000 ft^2 of treatment.

TABLE 34. AMMONIA-NITROGEN CONCENTRATION BY STAGE OF TREATMENT FOR HYDRAULIC BAY EXPERIMENTS

Experiment[a]	Day number[b]	Stage of treatment								
		I	1	2	3	4	5	6	7	E
		NH_3-N, mg/L								
2[c]	16	13	-	-	-	-	-	-	-	0.2
	19	15	-	-	-	-	-	-	-	0.2
	21	-	-	-	-	-	-	-	-	-
4[c]	19	8.1	8.1	7.9	7.3	6.0	4.6	-	2.1	-
	21	17	18	18	18	19	16	-	12	13
5[c]	16	15	16	16	14	13	12.0	-	12	10
	18	11	12	9.1	10	9.4	8.9	-	6.7	5.3
6	4	10	11	11.0	10	9.8	-	-	7.7	8.4
7	9	14	-	-	13	11	-	11	9.2	8.3
	14	16	16	16	15	15	-	13	12	10
8	9	12	15	13	13	12	-	11	10	7.7
	17	20	20	20	19	19	-	19	17	18
9	20	7.4	7.7	7.4	6.0	5.6	-	5.2	5.2	6.9
	21	6.2	6.8	5.7	5.6	5.6	-	5.2	5.2	4.6
13	8	8.0	6.8	4.9	3.9	3.2	-	0.0	0.0	0.0
	13	12	9.8	9.2	8.0	5.5	-	3.0	1.2	0.0
14	8	7.1	3.0	0.8	0.2	0.2	-	0.2	0.2	0.9
	10	9.5	0.2	4.3	0.8	0.2	-	0.2	0.2	0.2

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[a] no ammonia-nitrogen analysis was conducted for Experiment 3

[b] experiment day number when water sample was collected for analysis

[c] stage 1 in the hydraulic bay was inoperable for this experiment

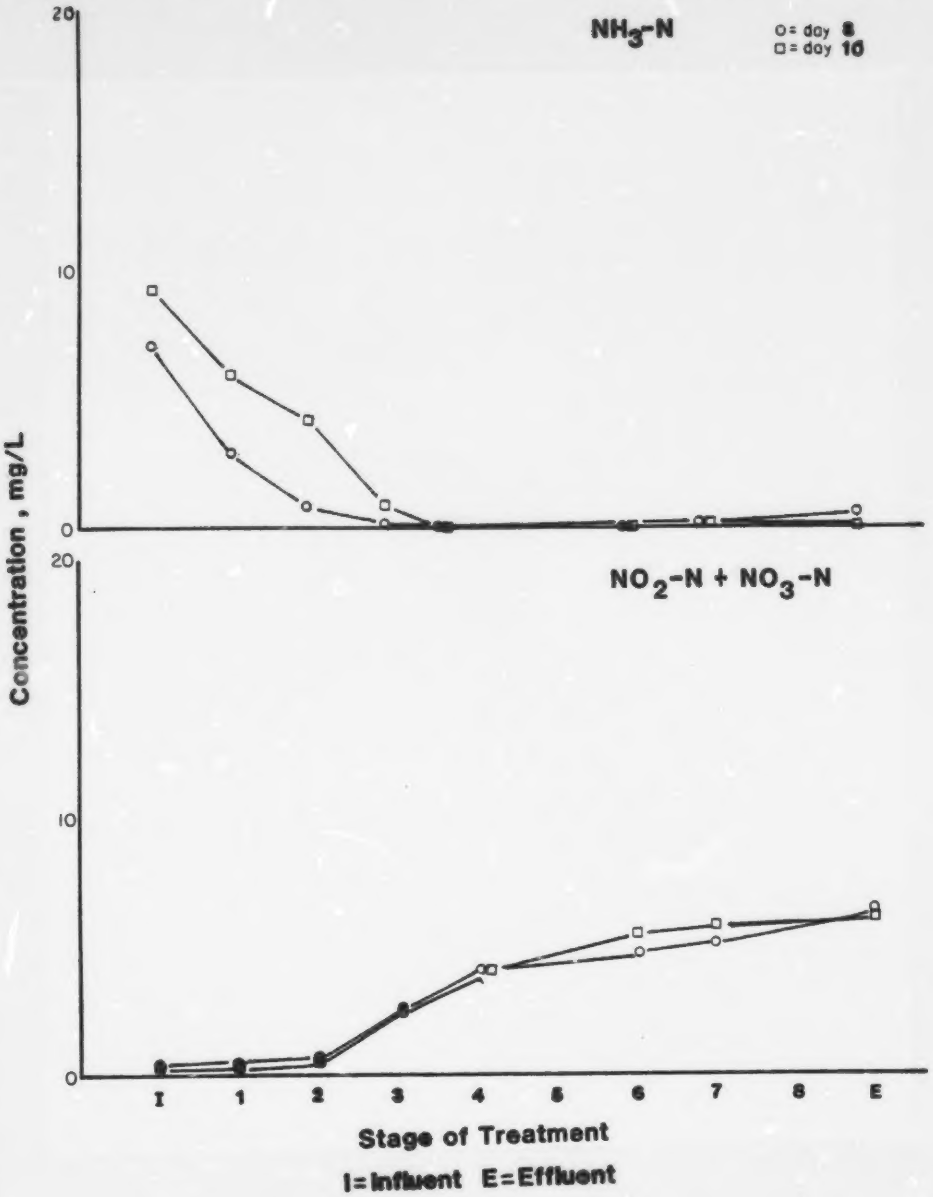

Figure 31. Concentration of nitrogen species versus stage of treatment for hydraulic bay Experiment 14, 50% of design flow.

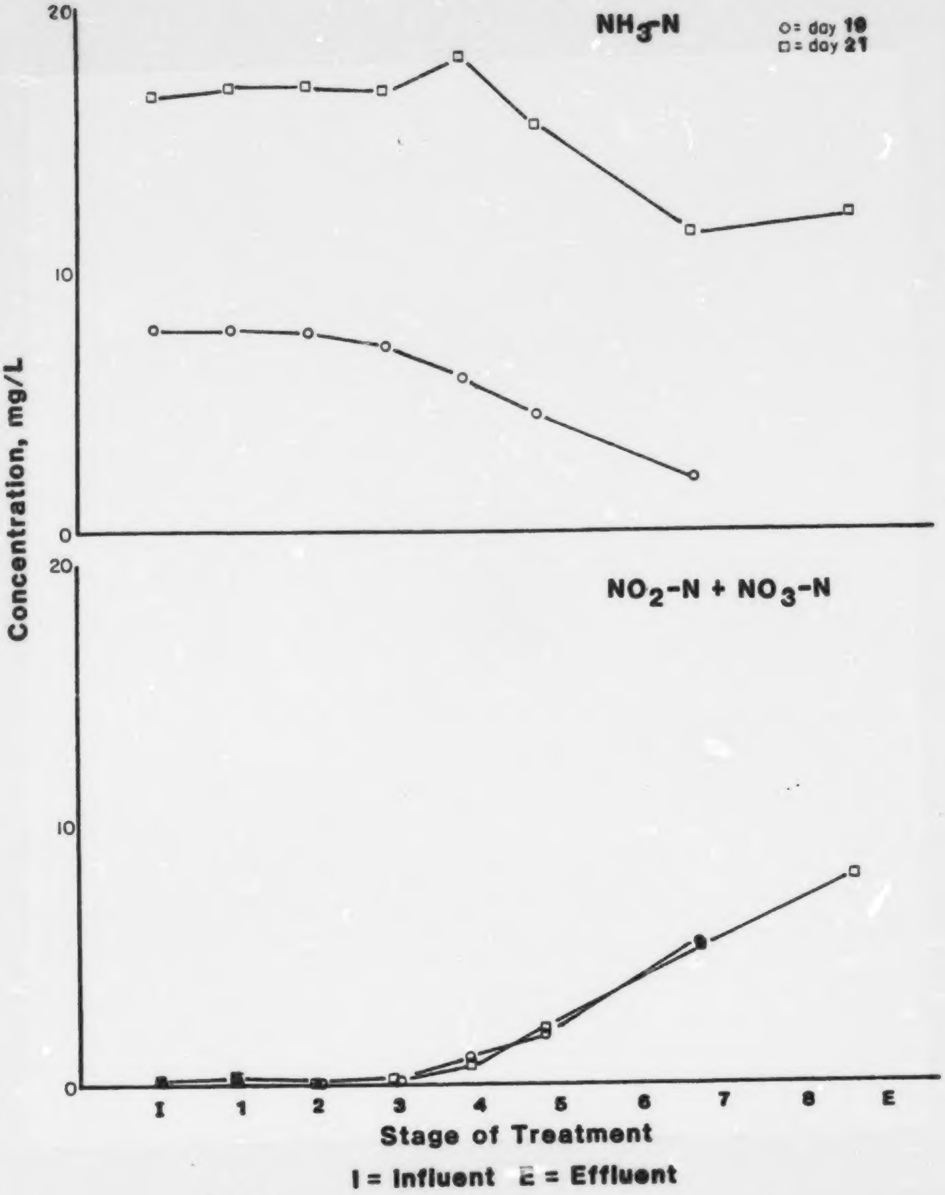

Figure 32. Concentration of nitrogen species versus stage of treatment for hydraulic bay Experiment 4, 100% of design flow.

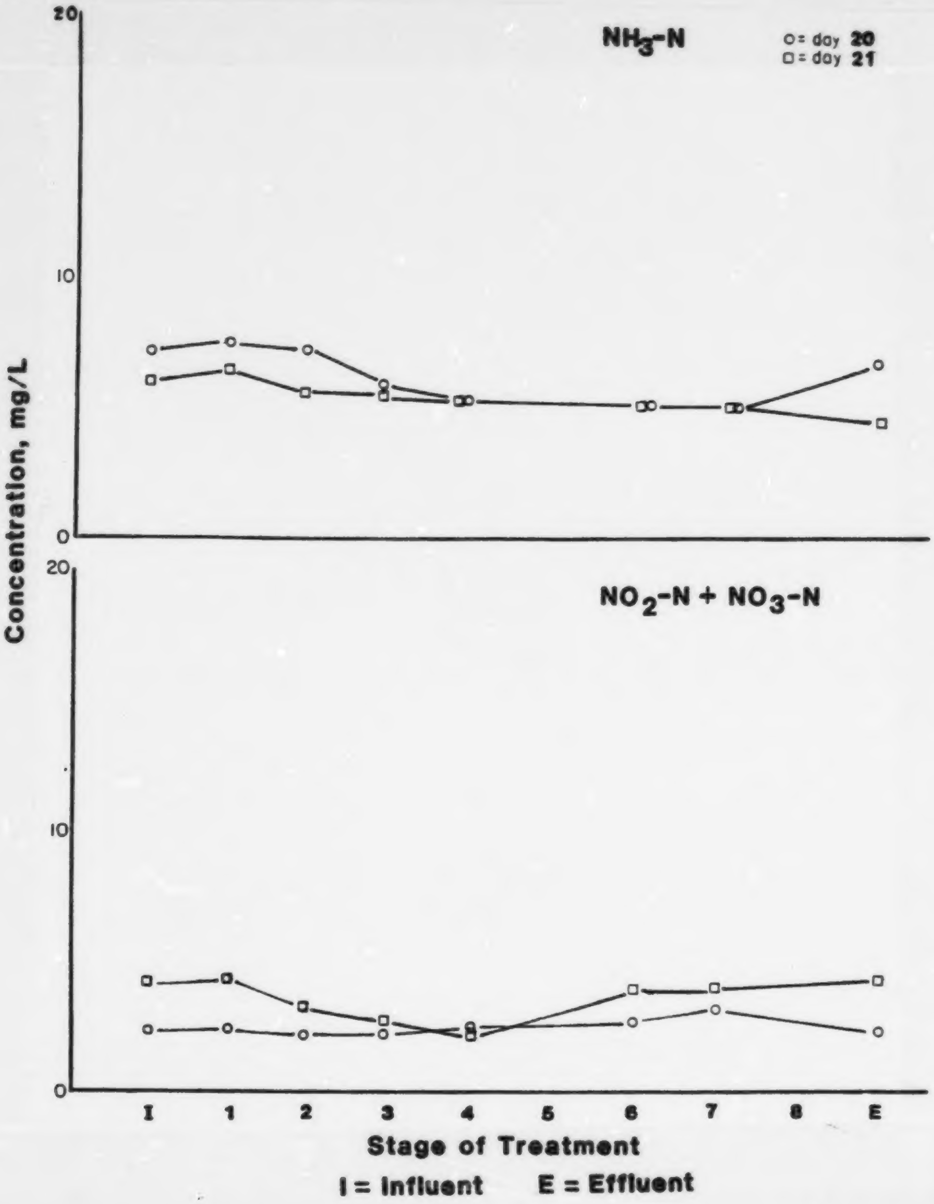

Figure 33. Concentration of nitrogen species versus stage of treatment for hydraulic bay Experiment 9, 200% of design flow.

TABLE 35. CUMULATIVE REDUCTION OF AMMONIA-NITROGEN CONCENTRATIONS FOR HYDRAULIC BAY EXPERIMENTS

Experiment[a]	Experiment (as percent of design flow)	Day number[b]	Percent removal
2[c]	50	16	98
		19	98
		21	-
4[c]	100	19	-
5[c]	125	16	31
		18	53
6	125	4	19
7	150	9	42
		14	34
8	175	9	36
		17	11
9	200	20	7
		21	26
13	75	8	100
		13	100
14	50	8	87
		10	98

[a] ammonia-nitrogen data was not collected for Experiment 3

[b] experiment day number when water sample was collected for analysis

[c] stage 1 in the hydraulic bay was inoperable for this experiment

TABLE 36. AMMONIA - NITROGEN CONCENTRATION BY STAGE OF TREATMENT FOR ORGANIC BAY EXPERIMENTS

Experiment[a]	Day number[b]	Stage of treatment				
		I[c]	1	2	3	E[d]
			NH_3-N, mg/L			
2	16	13	-	-	-	1.4
	19	15	-	-	-	0.2
	21	-	-	-	-	-
4	19	8	6.1	2.7	1.6	0.4
	21	17	18	13	9.7	11
5	16	15	16	13	11	9.9
	18	11	8.6	6.5	4.7	4.1
6	4	10	11	7.8	7.3	7.0
10	9	12	12	11	9.5	7.1
	11	9.8	9.2	7.7	6.7	6.0
11	9	14	12	10	10	9.6
	11	13	13	12	11	10
12	9	12	11	8.8	9.2	8.5
	14	11	9.6	9.8	9.6	8.3
12A	1	12	9.2	6.2	6.2	6.2
	2	7.7	6.8	5.8	4.8	4.3
	3	8.0	5.7	4.3	3.7	3.2
	6	9.2	6.6	4.2	3.5	-
13	8	8.0	3.9	0.2	0	0
	13	12	8.3	2.3	0.7	0
14	8	7.1	0.2	0.2	0.2	0.2
	10	9.5	0.6	0.2	0.2	0.2
14A	1	8.6	0.6	3.5	3.9	4.1
	2	9.9	8.0	5.3	6.2	6.3
	3	9.2	7.7	5.8	5.7	5.4

[a] ammonia-nitrogen data was not collected for Experiment 3

[b] experiment day number when water sample was collected for analysis

[c] influent

[d] effluent

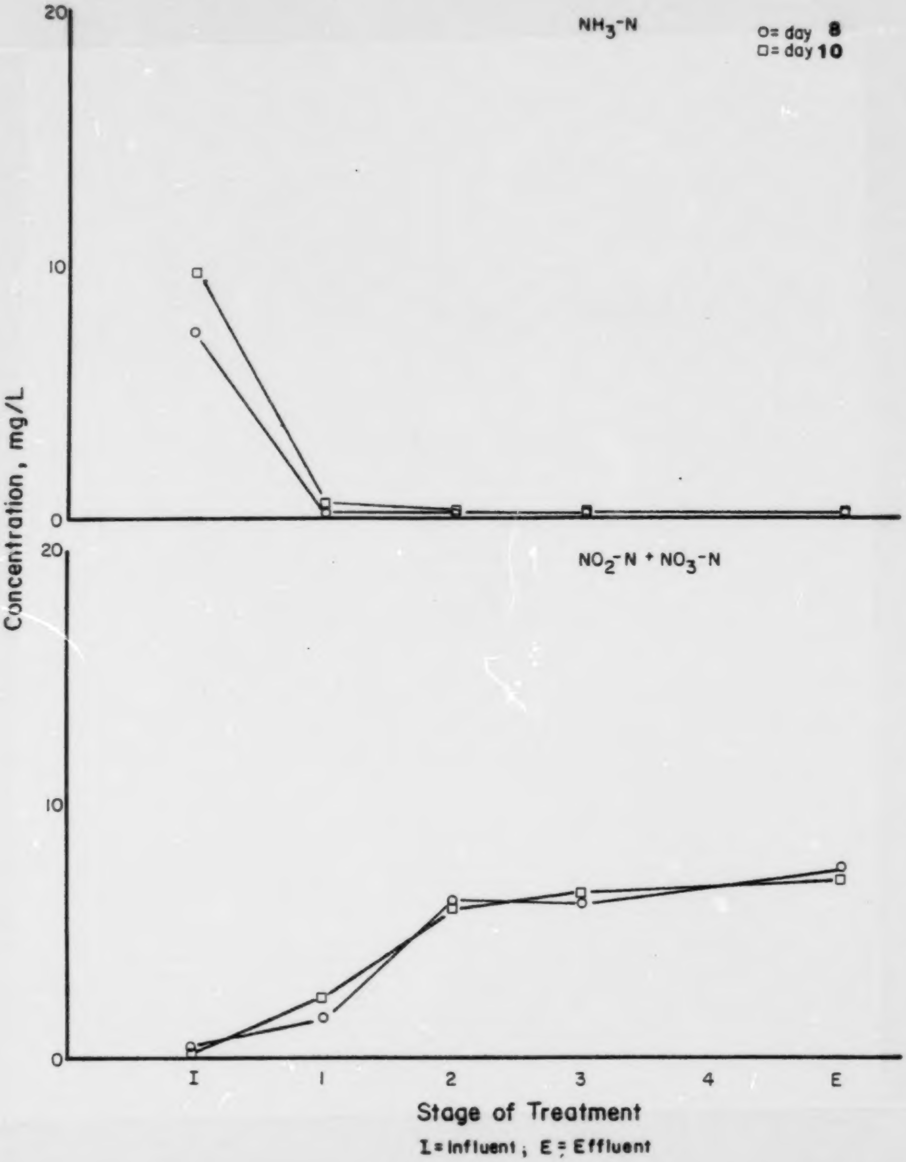

Figure 34. Concentration of nitrogen species versus stage of treatment for organic bay Experiment 14, 50% of design flow.

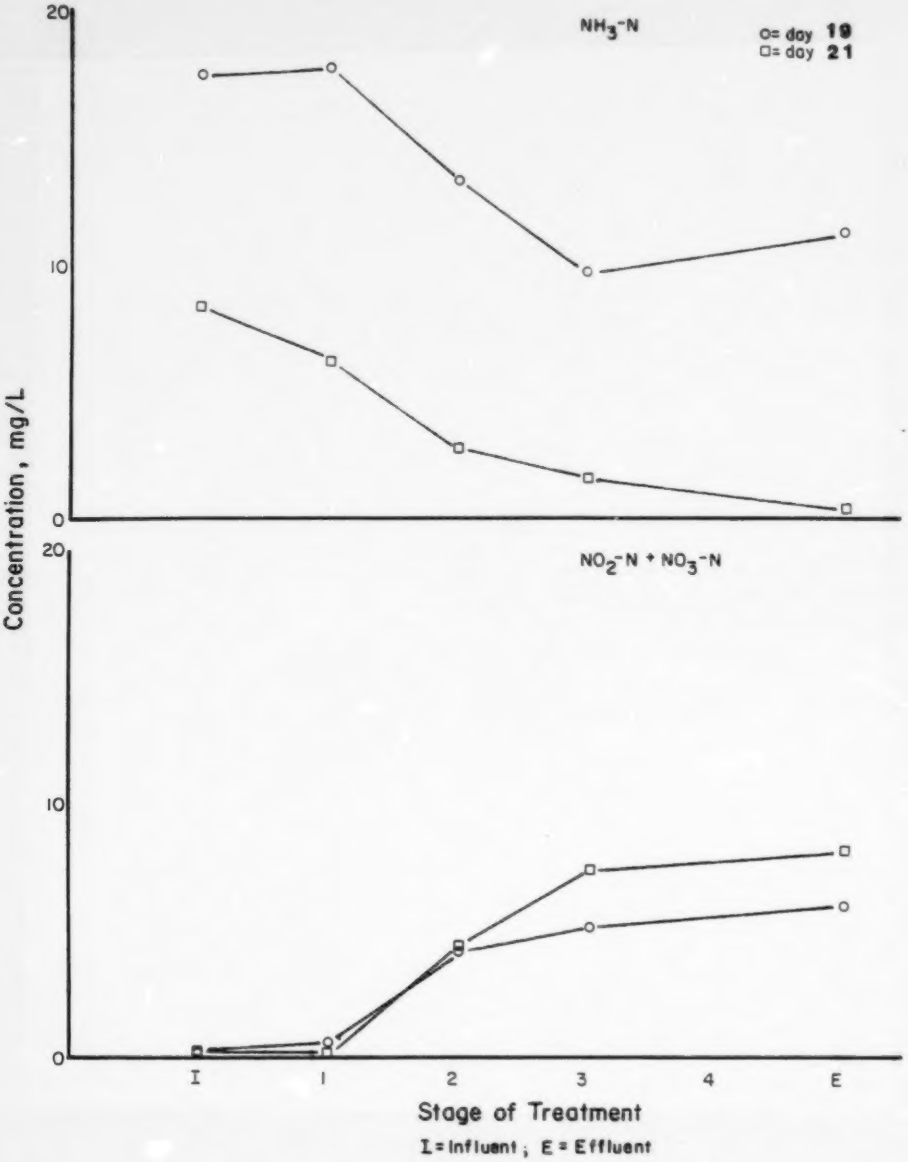

Figure 35. Concentration of nitrogen species versus stage of treatment for organic bay Experiment 4, 100% of design flow.

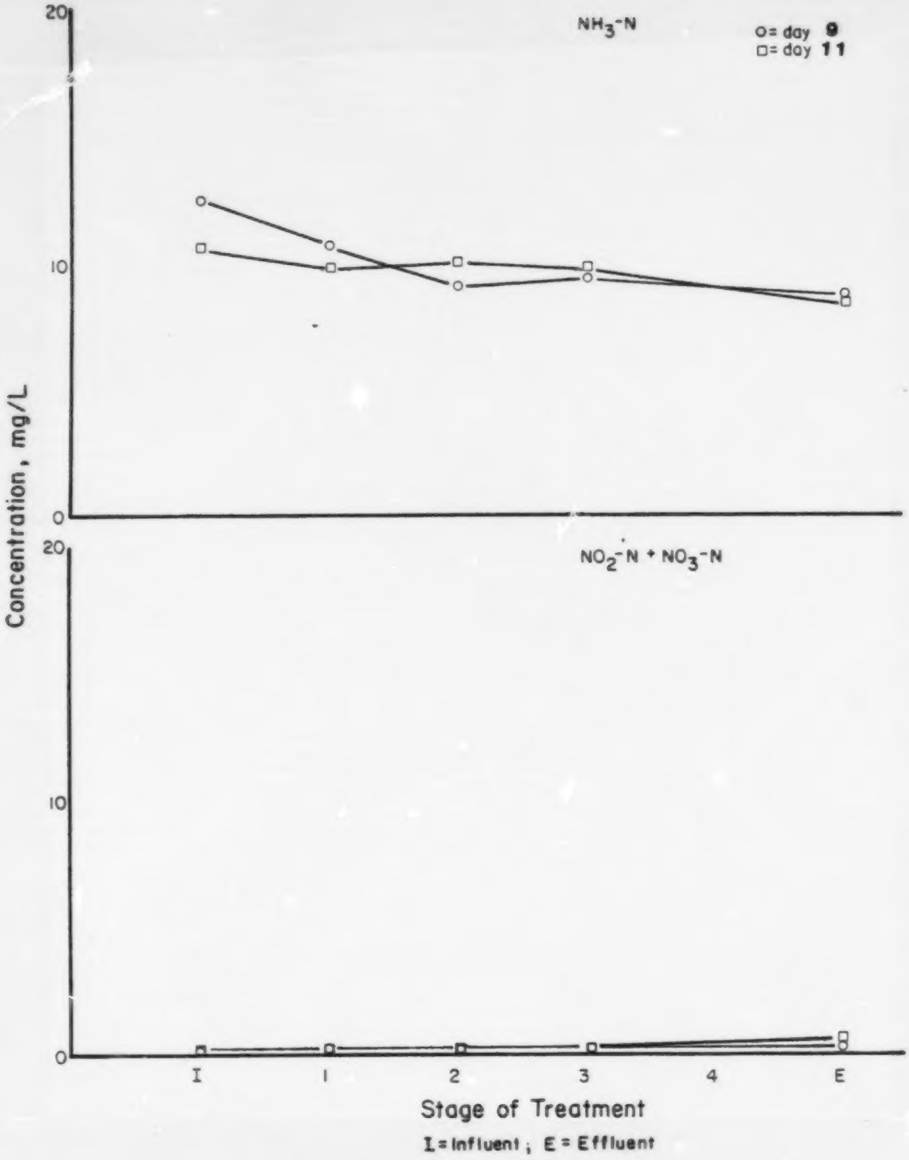

Figure 36. Concentration of nitrogen species versus stage of treatment for organic bay Experiment 12, 200% of design flow.

TABLE 37. CUMULATIVE REDUCTION OF AMMONIA-NITROGEN CONCENTRATIONS FOR ORGANIC BAY EXPERIMENTS

Experiment[a]	Percent of design flow	Day number[b]	Percent removal
2	50	16	88
		19	99
		21	-
4	100	19	95
		21	34
5	125	16	34
		18	64
6	125	4	30
10	150	9	39
		11	39
11	175	9	31
		11	23
12	200	9	30
		14	21
12A	75	1	50
		2	44
		3	60
		6	-
13	75	8	100
		13	100
14	50	8	97
		10	98
14A	200	1	52
		2	36
		3	41

[a] no ammonia - nitrogen analysis was conducted for Experiment 3

[b] experiment day number when water sample was collected for analysis

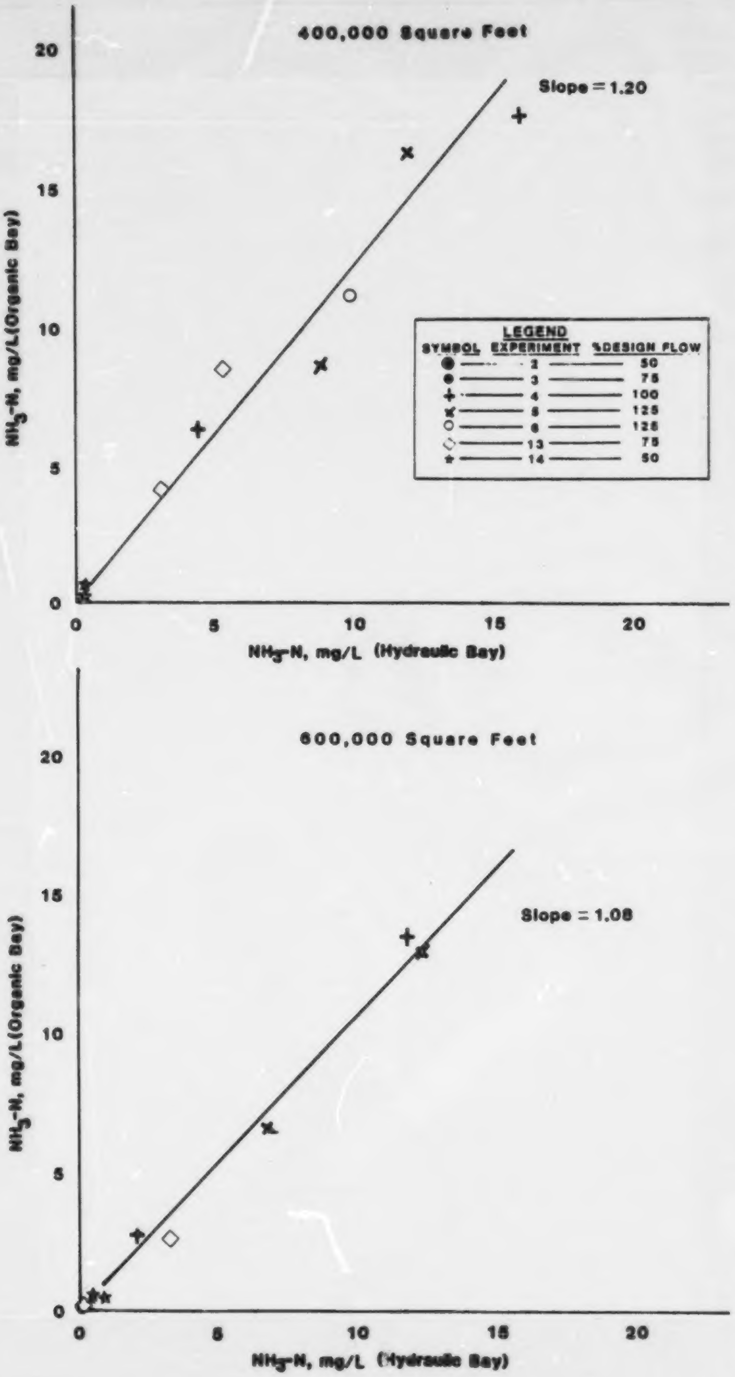

Figure 37. Ammonia-nitrogen concentrations for organic bay versus hydraulic bay after 400,000 ft^2 and 600,000 ft^2 of treatment.

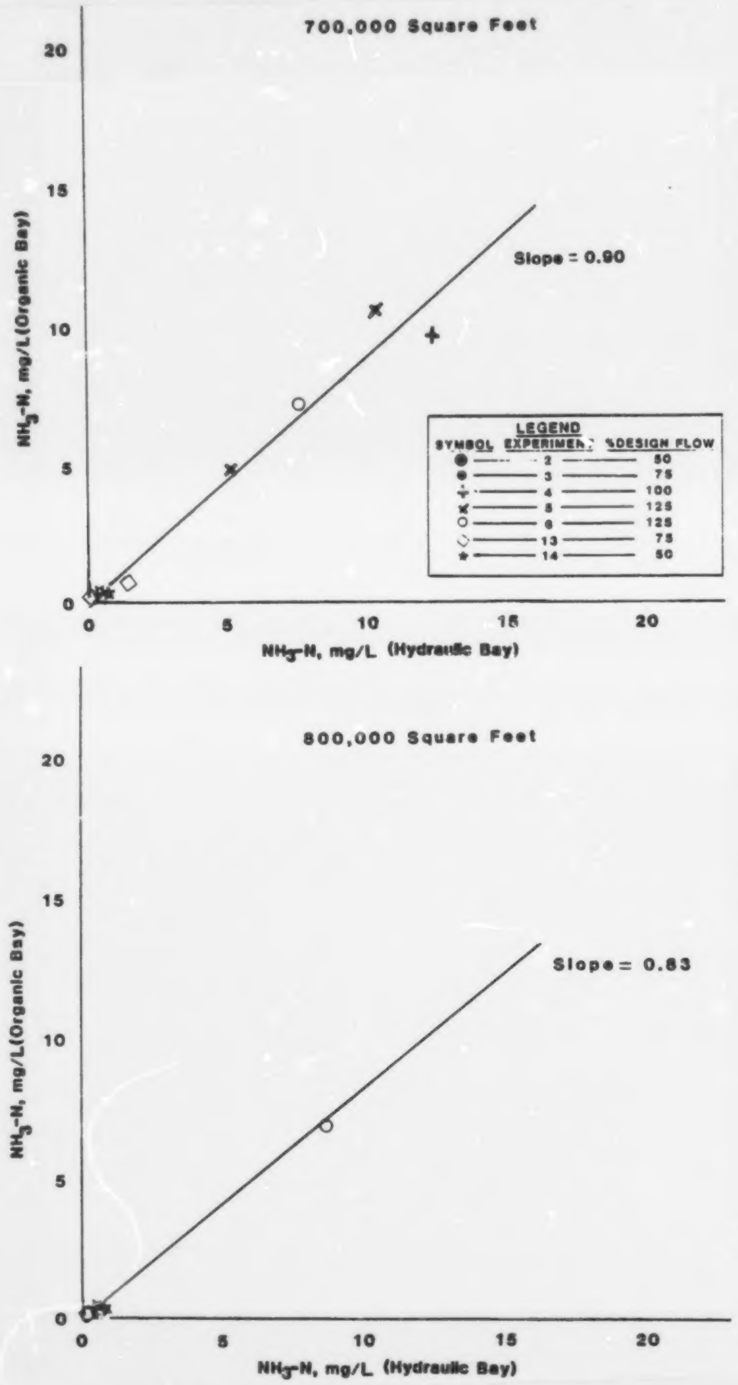

Figure 38. Ammonia-nitrogen concentrations for organic bay versus hydraulic bay after 700,000 ft^2 and 800,000 ft^2 of treatment.

TABLE 38. PAIRED T-TEST COMPARISON OF AMMONIA-NITROGEN CONCENTRATIONS IN HYDRAULIC AND ORGANIC BAYS

Treatment surface area	Tail area probability
400,000 ft^2	0.021[a]
600,000 ft^2	0.046[a]
700,000 ft^2	0.36[b]
800,000 ft^2	0.86[b]

[a] mean ammonia-nitrogen concentration was greater in the organic bay

[b] mean ammonia-nitrogen concentration was greater in the hydraulic bay

and 800,000 ft^2 there were no statistical differences between the ammonia-nitrogen concentrations in the organic and hydraulic bays although the observed concentrations were lower in the organic bay.

In Figure 39 ammonia-nitrogen concentrations for the period immediately following a change in flowrate from 200% of design flow to 75% of design flow in the organic bay are shown. The effluent ammonia-nitrogen levels appeared to be decreasing the first three days after the change in flowrate, indicating the return of the nitrification process. This is a confirming indication that the nitrifying organisms remained in the biofilms at 200% design flow and were ready to reestablish nitrification once the environmental conditions were satisfactory.

In Experiment 14A, the period of acclimation followed a flowrate change from 50% to 200% of design flow in the organic bay (Figure 40). The concentrations of ammonia-nitrogen were higher in each stage of treatment after the first day of acclimation, possibly due to the competition of the higher concentrations of cBOD or the reduced hydraulic retention time.

NITRITE-NITROGEN AND NITRATE-NITROGEN

Nitrite-nitrogen concentrations by stage of treatment for hydraulic bay experiments are presented in Table 39. The influent concentration varied from 0.02 mg/L to 0.05 mg/L on all occasions, except two observations of 0.25 mg/L and one observation of 1.4 mg/L. The concentration generally began to increase by stage 4 and continued to increase through the final stages. Effluent concentrations ranged from 0.04 mg/L during experiment 14 to 0.63 mg/L during Experiment 3.

Nitrate-nitrogen data by stage of treatment are presented in Table 40. Influent concentrations ranged from 0.1 mg/L on several occasions to 4.2 mg/L during Experiment 9. At lower flowrates the nitrate-nitrogen concentration increased markedly through successive stages, beginning about stage 4. At 200% of design flow (Experiment 9) little change in concentration occurred

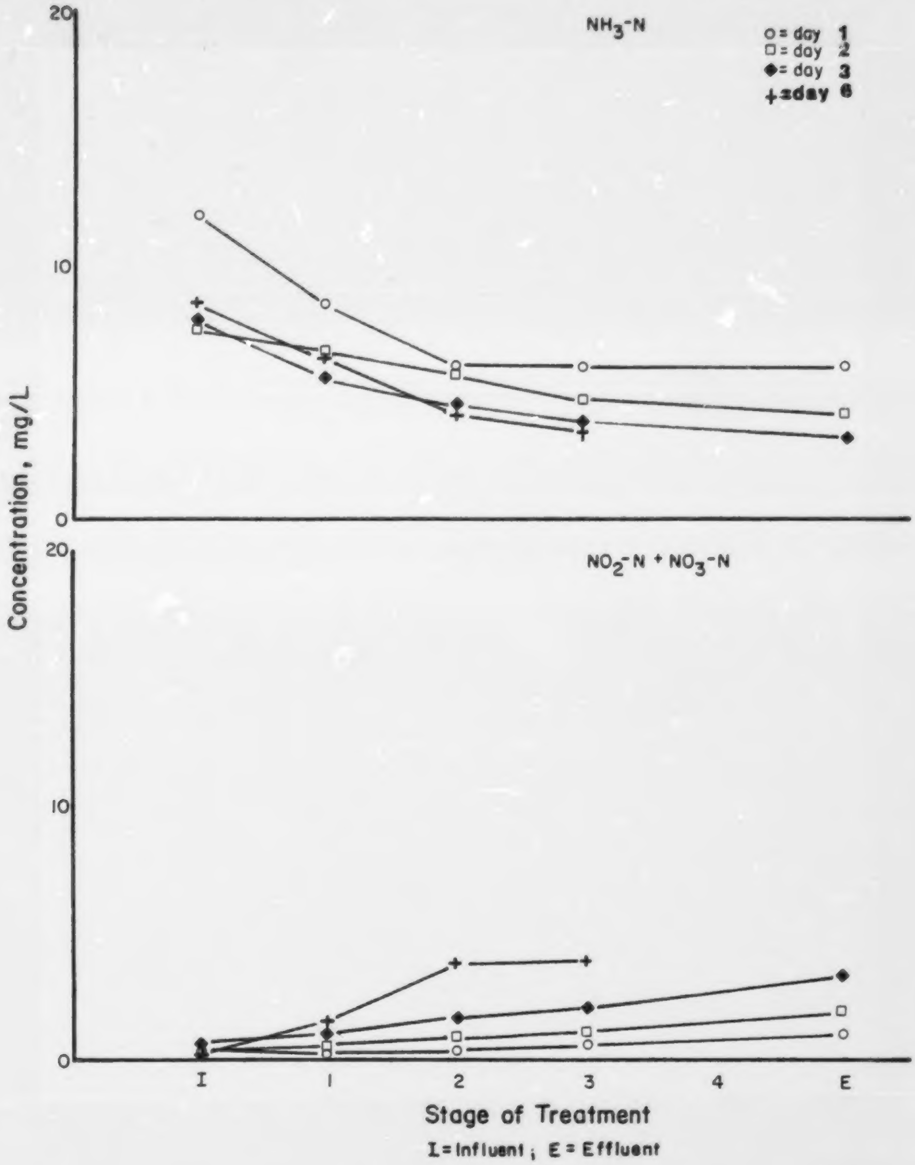

Figure 39. Concentration of nitrogen species versus stage of treatment for organic bay Experiment 12A, 75% of design flow.

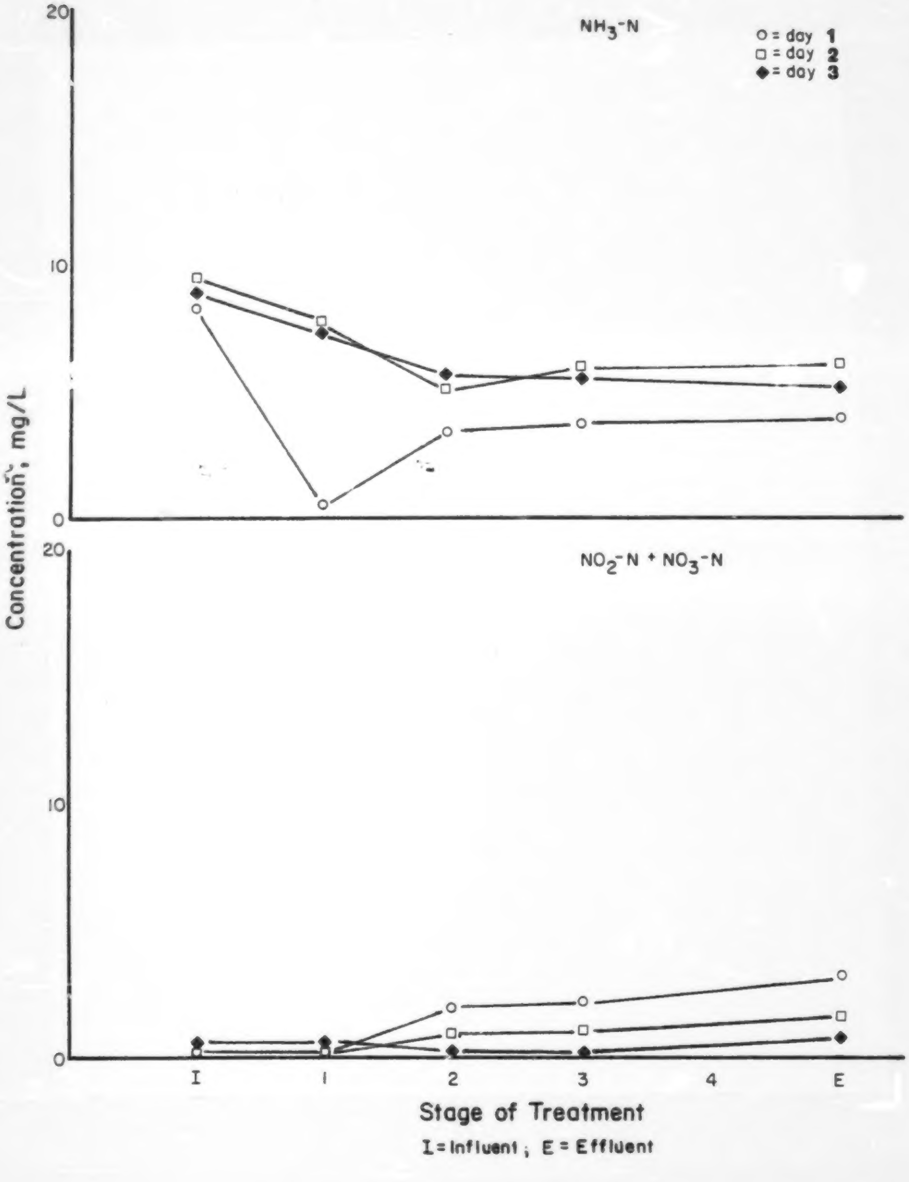

Figure 40. Concentration of nitrogen species versus stage of treatment for organic bay Experiment 14A, 200% of design flow.

TABLE 39. NITRITE-NITROGEN CONCENTRATION BY STAGE OF TREATMENT FOR HYDRAULIC BAY EXPERIMENTS

Experiment[a]	Day number[b]	Stage of treatment I	1	2	3	4	5	6	7	E
					NO_2-N, mg/L					
3c	17	0.05	0.05	0.05	0.05	0.06	0.14	-	0.48	0.63
	18	0.05	-	-	-	-	-	-	-	0.56
4c	19	0.05	0.05	0.05	0.05	0.37	0.35	-	0.38	-
	21	0.05	0.05	0.05	0.05	0.41	0.40	-	0.40	0.52
5c	16	0.05	0.05	0.05	0.05	0.05	0.05	-	0.36	0.36
	18	0.05	0.05	0.05	0.05	0.05	0.05	-	0.19	0.33
6	4	0.25	0.05	0.05	0.05	0.05	-	0.12	0.26	0.36
7	9	0.05	0.05	0.05	0.05	0.05	-	0.18	0.26	0.46
	14	0.05	0.05	0.05	0.12	0.25	-	0.25	0.34	0.46
8	9	0.05	0.05	0.05	0.58	0.45	-	0.33	0.47	0.50
	17	0.05	0.05	0.05	0.05	0.05	-	0.46	0.44	0.58
9	20	1.4	0.87	0.83	0.45	0.30	-	0.30	0.31	0.48
	21	0.25	0.27	0.56	0.85	0.88	-	0.37	0.43	0.35
13	8	0.02	0.02	0.02	0.17	0.32	-	0.31	0.20	0.19
	13	0.02	0.02	0.02	0.30	0.36	-	0.40	0.36	0.20
14	8	0.02	0.02	0.26	0.32	0.26	-	0.13	0.12	0.04
	10	0.02	0.02	0.25	0.28	0.26	-	0.16	0.13	0.05

[a] no nitrite-nitrogen analysis was conducted for Experiment 2

[b] experiment day number when water sample was collected for analysis

[c] stage 1 in the hydraulic bay was inoperable for this experiment

TABLE 40. NITRATE-NITROGEN CONCENTRATION BY STAGE OF TREATMENT FOR HYDRAULIC BAY EXPERIMENTS

Experiment	Day number[a]	Stage of treatment								
		I	1	2	3	4	5	6	7	E
						NO_3-N, mg/L				
2	16	1.4	-	-	-	-	-	-	-	12.9
	19	0.9	-	-	-	-	-	-	-	13.2
	21	0.7	-	-	-	-	-	-	-	17.8
3	17	0.2	0.2	0.2	0.2	0.4	1.5	-	4.7	6.7
	18	0.2	-	-	-	-	-	-	-	6.5
4	19	0.1	0.1	0.1	0.1	0.7	1.8	-	5.2	-
	21	0.1	0.2	0.1	0.1	0.4	1.8	-	5.1	7.7
5	16	0.2	0.2	0.2	0.3	0.2	0.2	-	2.7	4.3
	18	0.2	0.2	0.2	0.2	0.2	0.2	-	1.3	2.0
6	4	0.4	0.2	1.8	0.6	0.2	-	0.7	1.5	1.9
7	9	-	0.1	0.2	0.2	0.2	-	0.8	1.4	2.1
	14	0.2	0.2	0.2	0.2	0.3	-	0.9	1.8	2.3
8	9	0.2	0.2	0.2	0.2	0.2	-	1.5	2.2	3.1
	17	0.1	0.1	0.1	0.1	0.1	-	0.7	1.1	1.4
9	20	1.0	1.6	1.3	1.8	2.2	-	2.6	2.9	2.0
	21	4.2	4.2	2.8	1.9	1.5	-	3.7	3.7	4.0
13	8	0.2	0.2	0.2	0.6	1.4	-	3.5	4.7	5.7
	13	0.2	0.2	0.2	1.0	2.1	-	5.1	6.5	7.7
14	8	0.2	0.2	0.4	2.3	3.8	-	4.8	5.1	6.6
	10	0.1	0.1	0.3	2.2	3.8	-	5.3	5.8	6.2

[a] experiment day number when water sample was collected for analysis

though the treatment train, with effluent concentrations very similar to influent values. Effluent nitrate-nitrogen concentration varied from 1.4 mg/L during Experiment 8 (175% of design flow) to 18 mg/L during Experiment 2 (50% of design flow).

Since nitrite-nitrogen and nitrate-nitrogen are both produced by the nitrification process, their concentrations were summed for graphic analysis. Figures 31, 32, and 33 present these combined concentrations versus stage of treatment for 50%, 100%, and 200% of design flow hydraulic bay experiments, respectively. At 50% of design flow the production of nitrite-nitrogen and nitrate-nitrogen began in stage 3 and continued throughout the sucessive stages. At 100% of design flow the production of nitrite-nitrogen and nitrate-nitrogen was pushed back to the fourth stage of treatment because of increased hydraulic and organic loading (Figure 32). At 200% of design flow there was no production of nitrite-nitrogen and nitrate-nitrogen.

In Table 41 the nitrite-nitrogen concentrations in the organic bay are presented. The influent ranged from 0.02 mg/L to 0.05 mg/L on all but one occasion when the concentration was 0.25 mg/L. In the low flow experiments the concentration of nitrite-nitrogen usually peaked in one of the first three stages and then began to decrease. The highest concentration reported was 0.62 mg/L in the second stage of treatment at 75% of design flow. In the higher flowrate experiments the nitrite-nitrogen concentrations were generally highest in the effluent. Effluent concentrations varied from 0.04 mg/L at 50% of design flow to 0.54 mg/L, at 75% of design flow.

The nitrate-nitrogen data are presented in Table 42 for the organic bay experiments. The influent nitrate-nitrogen concentration ranged from 0.1 mg/L to 0.4 mg/L except during Experiment 2. In Experiment 2 the influent concentrations ranged from 0.7 mg/L to 1.4 mg/L. Below 100% of design flow the nitrate concentration began to increase in the first stage and continued to increase in each stage of treatment. As the flowrate was increased the nitrate concentration failed to increase in the early stages of treatment. At 200% of design flow (Experiment 12) the effluent concentration was only 0.1 to 0.3 mg/L greater than the influent. The nitrate-nitrogen concentration in the effluent was lowest at 200% of design flow with a concentration of 0.2 mg/L and greatest at 50% of design flow (Experiment 2) with concentrations up to 19 mg/L.

Figures 34, 35, and 36 show the combined concentration of nitrite-nitrogen and nitrate-nitrogen versus stage of treatment for organic bay experiments at 50%, 100%, and 200% of design flow, respectively. A general trend of increasing nitrite-nitrogen plus nitrate-nitrogen concentration through the treatment train was observed. At 50% of design flow the increase was observed in the first stage of treatment. At 100% of design flow the concentration remained approximately constant until the second stage of treatment, where it began to increase. At 200% of design flow the combined nitrite-nitrogen and nitrate-nitrogen concentration in the effluent had increased only slightly above the influent concentration.

TABLE 41. NITRITE-NITROGEN CONCENTRATION BY STAGE OF TREATMENT FOR ORGANIC BAY EXPERIMENTS

Experiment[a]	Day	Stage of treatment				
	number[b]	I	1	2	3	E
			NO_2-N, mg/L			
3	17	0.05	0.26	0.53	0.55	0.54
	18	0.05	-	-	-	0.48
4	19	0.05	0.44	0.41	0.40	0.33
	21	0.05	0.05	0.56	0.59	0.47
5	16	0.05	0.05	0.36	0.50	0.48
	18	0.05	0.05	0.20	0.27	0.45
6	4	0.25	0.05	0.27	0.35	0.38
10	9	0.04	0.02	0.39	0.42	0.45
	11	0.02	0.02	0.02	0.17	0.32
11	9	0.02	0.02	0.02	0.02	0.21
	11	0.02	0.02	0.02	0.02	0.16
12	9	0.02	0.02	0.02	0.02	0.21
	14	0.02	0.02	0.02	0.02	0.17
12A	1	0.02	0.02	0.11	0.11	0.24
	2	0.02	0.13	0.14	0.15	0.26
	3	0.02	0.16	0.25	0.25	0.30
	6	0.02	0.34	0.53	0.61	-
13	8	0.02	0.23	0.37	0.36	0.28
	13	0.02	0.49	0.62	0.56	0.34
14	8	0.02	0.38	0.21	0.16	0.04
	10	0.02	0.48	0.22	0.14	0.07
14A	1	0.02	0.02	0.47	0.43	0.53
	2	0.02	0.02	0.32	0.42	0.43
	3	0.02	0.02	0.03	0.02	0.23

[a] nitrite-nitrogen data was not collected for Experiment 2

[b] experiment day number when water sample was collected for analysis

TABLE 42. NITRATE-NITROGEN CONCENTRATION BY STAGE OF TREATMENT FOR ORGANIC BAY EXPERIMENTS

Experiment	Day number[a]	Stage of treatment				
		I	1	2	3	E
		NO$_3$-N,mg/L				
2	16	1.4	-	-	-	12.4
	19	0.9	-	-	-	13.2
	21	0.7	-	-	-	19.1
3	17	0.2	0.5	4.2	5.9	7.8
	18	0.2	-	-	-	8.4
4	19	0.1	0.2	4.0	5.0	5.8
	21	0.1	0.1	3.9	7.1	7.8
5	16	0.2	0.2	2.2	2.9	3.1
	18	0.2	0.2	1.3	1.8	2.4
6	4	0.4	0.2	1.4	1.9	2.7
10	9	0.1	0.1	1.0	2.2	3.7
	11	0.1	0.1	0.2	0.7	1.3
11	9	0.1	0.1	0.1	0.1	0.9
	11	0.1	0.1	0.1	0.1	0.7
12	9	0.1	0.1	0.1	0.1	0.2
	14	0.1	0.1	0.1	0.1	0.4
12A	1	0.1	0.1	0.4	0.6	0.8
	2	0.1	0.4	0.8	1.0	1.7
	3	0.1	0.8	1.3	1.8	3.0
	6	0.1	1.2	3.3	3.4	-
13	8	0.2	0.7	2.8	3.7	4.4
	13	0.2	1.2	6.1	7.0	7.6
14	8	0.2	1.3	5.8	6.0	7.6
	10	0.1	1.7	5.9	6.5	7.0
14A	1	0.3	0.3	1.5	1.9	2.8
	2	0.1	0.1	0.7	0.8	1.4
	3	0.1	0.1	0.1	0.1	0.7

[a] experiment day number when water sample was collected for analysis

Figure 39 shows that the concentration of nitrite-nitrogen and nitrate-nitrogen increased each day following the change in flow from 200% to 75% of design flowrate (Experiment 12A). This indicates that nitrifying organisms were already present in all stages of the treatment train since there was no time lag before measurable nitrification began after the flow was reduced. Conversely, in Figure 40 the acclimatization following an increase in flow is shown for Experiment 14A. The levels of nitrite-nitrogen and nitrate-nitrogen were reduced each day following the change in flowrate indicating that the nitrifiers were less able to accomplish nitrification under the environmental conditions associated with the higher flow experiment.

ORGANIC-NITROGEN

In Table 43, the total organic-nitrogen concentrations are presented. The influent concentrations ranged from 1.7 mg/L in Experiment 9 to 11.7 mg/L in Experiment 5. The concentration in the effluent was always less than in the influent. The hydraulic bay effluent organic-nitrogen concentrations varied from 1.4 mg/L at 50% of design flow (Experiment 14) to 4.9 mg/L at 200% of design flow (Experiment 9). Organic-nitrogen in the effluent of the organic bay ranged from 1.7 mg/L at 50% of design flow (Experiment 14) to 5.8 mg/L at 175% (Experiment 11) and 200% of design flow (Experiment 12). Generally, the concentration of organic nitrogen in the effluent increased as the flowrate increased although the trend was less apparent in the hydraulic bay.

TOTAL NITROGEN SPECIES

In order to understand nitrogen cycling in the system a complete analysis of nitrogen species was performed during Experiment 14. Ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, and soluble organic-nitrogen were measured. The biomass-nitrogen component was determined to be 12.4% of the volatile suspended solids based upon an empirical formula of $C_5H_7O_2N$. The sum of these five constituents was total nitrogen. It was assumed that the nitrogen content of the biomass on the shafts was not changing. Thus, any change in total nitrogen represented losses from or inputs into the system. These data are presented in Table 44 for the hydraulic and organic bays, respectively.

Both bays exhibited a rapid decrease in ammonia-nitrogen concentrations in the early stages of treatment. These reductions in ammonia-nitrogen concentrations were not immediately balanced by increased nitrite-nitrogen or nitrate-nitrogen concentrations, suggesting a loss of nitrogen from the system. The early stages exhibited lower dissolved oxygen concentrations and higher organic-nitrogen concentrations. These conditions favor denitrification which would convert ammonia-nitrogen to nitrite-nitrogen followed by rapid reduction to molecular nitrogen (N_2) and loss to the atmosphere. The increases in dissolved oxygen in later stages corresponded to the build up of nitrite-nitrogen followed by nitrate-nitrogen. These observations are consistent with the proposal that denitrification and nitrification were occurring in the treatment train. In addition, the decreasing soluble organic nitrogen concentrations suggest that organic

TABLE 43. ORGANIC-NITROGEN CONCENTRATION FOR HYDRAULIC AND ORGANIC BAY EXPERIMENTS

Experiment[a]	Percent design flow	Day number[b]	Influent	Hydraulic bay effluent	Organic bay effluent
				Organic-N, mg/L	
4c	100	19	6.7	-	2.5
		21	9.1	2.7	1.9
5c	125	16	12	3.0	2.5
		18	12	-	2.0
6	125	4	9.1	3.6	2.0
7	150	9	5.8	4.6	-
		14	8.0	3.6	-
8	175	9	7.7	1.9	-
		17	7.7	1.9	-
9	200	20	6.2	4.9	-
		21	1.7	3.7	-
10	150	9	8.0	-	3.7
		11	8.6	-	3.8
11	175	9	6.5	-	2.5
		11	8.6	-	5.8
12	200	9	10	-	4.9
		14	8.6	-	5.8
12A	75	1	8.9	-	5.2
		2	7.8	-	3.8
		3	9.2	-	3.1
13	75	8	9.4	4.7	3.4
		13	8.8	2.2	3.3
14	50	8	9.5	1.5	1.8
		10	8.0	1.4	1.7
14A	200	1	8.3	-	3.3
		2	8.6	-	4.1
		3	9.5	-	5.1

[a] organic nitrogen data was not collected for Experiments 2 and 3

[b] experiment day number when sample was collected for analysis

[c] stage 1 of the hydraulic bay was inoperable for this experiment

TABLE 44. CONCENTRATIONS OF NITROGEN SPECIES AS NITROGEN, EXPERIMENT 14, 50% DESIGN FLOW, FOR MASS BALANCE ANALYSIS

		Day 8						Day 10					
		NH_3-N	NO_2-N	NO_3-N	SON-N	BN-N	TOTAL-N	NH_3-N	NO_2-N	NO_3-N	SON-N	BN-N	TOTAL-N
Stage of treatment							Concentration, mg/L						
Hydraulic bay	I	7.1	0.02	0.2	6.9	11	25	9.5	0.02	0.1	3.1	8.0	21
	1	3.0	0.02	0.2	5.5	-	-	6.2	0.02	0.1	2.9	-	-
	2	0.8	0.26	0.4	-	-	-	4.3	0.25	0.3	1.2	-	-
	3	0.2	0.32	2.3	3.3	0	0	0.8	0.28	2.2	3.5	-	-
	4	0.2	0.26	3.8	2.1	-	-	0.2	0.26	3.8	2.3	-	-
	6	0.2	0.13	4.8	1.9	11	18	0.2	0.16	5.3	1.4	8.4	16
	7	0.2	0.12	5.1	1.6	11	18	0.2	0.13	5.8	1.0	8.8	16
	E	0.9	0.04	6.6	0.8	12	19	0.2	0.05	6.2	-	11	
Organic bay	I	7.1	0.02	0.2	6.9	11	25	9.5	0.02	0.1	3.1	8.0	21
	1	0.2	0.38	1.3	4.7	-	-	0.6	0.48	1.7	4.0	-	-
	2	0.2	0.21	5.8	1.4	-	-	0.2	0.22	5.9	0.5	0	0
	3	0.2	0.16	6.0	1.2	10	18	0.2	0.14	6.5	1.4	9.0	17
	E	0.2	0.04	7.6	1.2	12	21	0.2	0.07	7.0	1.3	8.3	17

nitrogen was hydrolyzed to ammonia-nitrogen. More data would be needed to verify the presence of these three processes and to quantify their chemical transformations.

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APPENDIX A

COLUMBUS WASTEWATER TREATMENT PLANT DESIGN SUMMARY

DESIGN FLOWS

	Influent	Effluent
Flow, Average	12.4 MGD	12.4 MGD
Flow, Peak	18.0 MGD	18.0 MGD
cBOD	250	20
SS	370	20
NH_3-N	15	5 (winter)
PO_4	15	1 (summer only)

UNIT PROCESS

Comminution

Number of comminutors	3
Size, in.	25
HP, each	1 1/2
Maximum capacity, mgd each	10
Manufacturer	FMC

Raw Sewage Pumping

Number of pumps	4
Capacity, gpm-TDH in feet	5000-56
HP, each	100
Type	variable speed, centrifugal
Manufacturer	Allis-Chalmers

Raw Sewage Metering

Type	magnetic meter
Manufacturer	Brooks

Grit Removal

Number of tanks	2
Dimension L'xW'xSWD'	20x20x10.5
Volume, ft^3 total	7,400
Det. time, min. peak flow	4.4
Type	aerated
Manufacturer	Peabody

Grit Separator

Type	cyclone
Manufacturer	Wemco

Grit Pumping

Number of pumps	2
Capacity, gpm TDH in feet	200-40
HP, each	10

Type	torque
Manufacturer	Wemco

Preaeration

Number of tanks	1
Dimension, L'xW'xD'	47x20x12
Volume, ft^3	11,300
Det. time, min. @ 5 mgd	24
Type	diffused air

Primary Clarification

Number of tanks	5
Dimension, L'xW'xD'	88x33x11 (73.5x20x11)
Surface area, ft^2 total	10,200
Volume, ft^3 total	112,200
Overflow rate gpd/ft^2	1,200
Det. time, hr.	1.6
Type	rect. chain
Manufacturer	Sycamore

Primary Sludge Pumping

Number of pumps	5
Capacity, gpm TDH in ft.	2-300-40 1-300-30 1-50-40 1-75-50
HP, each	3-10 1-5 1-3
Type	torque, piston & plunger
Manufacturer	Wemco

Primary Effluent Pumps

Number of pumps	3
Size, inches	50
Capacity, gpm-lift in ft.	6200-4
HP, each	10
Type	screw
Manufacturer	EDC

Rotating Biological Reactors

Number of tanks	10
Number of reactors	80
Dim., L'xW'xD' ea. tank	119.33 x 26.33 x 5.92
Media area ft^2 total	8,000,000
Hydraulic rate, gpd/ft^2	1.6
Det. time, hrs.	2.0

HP, each	7.5
Manufacturer	Autotrol

CHEMICAL

Chlorination

Number of units	2
Capacity lb/24 hr.	1,500
Type	Auto control w/chlorine residual analyzer
Manufacturer	Wallace and Tiernan
Phosphate reduction	
Number of Pumps	2-5.5 gph for sodium alum. 2-104 gph for alum 2-104 gph for polymer

DIGESTION

Number of tanks	3
Size, diameter in feet	60
Volume, ft^3 each	74,000 (#1 & 2 primary dig.) 71,000 (#3 secondary dig.)
Sludge flow, gpd	62,600
Solids rate VSS/day	16,700
Hydraulic det. time, days for prim. digesters	37
Solids loading VSS/day/ 1000 ft^3 for prim. digesters	0.12
Cover type	Floating
Manufacturer	Carter

MIXING

Type	Pearth Gas Recirculation
Compressor capacity, cfm	150
Compressor size, HP	10
Number of discharge wells	5
Manufacturer	Carter

SOLAR UNIT

Size, ft^2	250
Type	Aluminum absorber plates
Manufacturer	Pittsburgh Plate Glass Co.

HEATING

Number of heat exchangers	3
Capacity of heat exchangers, BTU/Hr	2-1,000,000 (1,500,000)
Type	Counter flow - spiral
Manufacturer	Dorr-Oliver
Standby boiler cap. MBH	2,350
Type	Fine tube
Manufacturer	Dunham-Bush (Iron Fireman)

RECIRCULATION

Number of pumps	3
Capacity, gpm-TDH in ft	200 - 35
HP, each	10
Type	Torque
Manufacturer	Wemco

GAS PRODUCTION

ft^3/day @ 10 mgd	125,000

GAS STORAGE

Sphere size, dia. ft.	21.5
Volume ft^3	5,200

SLUDGE DEWATERING

Number of units	2
Capacity, gpd	2,600 & 1,300
Type	Sludge press
Manufacturer	Carter and Permutit

HEAT PUMPS

Number of units	5
Cooling capacity, BTU/H	2-12,500, 1-9,000 1-12,000, 1-64,000
Heating capacity, BTU/H	2-14,200, 1-8,500 1-11,000, 1-61,000
Type	Water - Air
Manufacturer	Koldwave Heat Ex., Inc.

FLASH MIXING

Propeller size, in.	15
HP	1
Type	vertical
Manufacturer	Mixing Eq. Co.

FLOCCULATION

Number of units	5
Dimension L'xW'xD'	58x 12x12
Volume, ft^3 total	8,400
Det. time, min.	7
Det. time, min. including pipe and aerated channel	12
Type	horizontal paddle
Paddle dia. ft.	10
Paddle distribution	8 @ 1st unit 6 @ 2nd & 3rd unit 4 @ 4th and 5th unit
Manufacturer	Sycamore

FINAL CLARIFICATION

Number of tanks	6
Dim., L'xW'xD'	2-145 x 30 (3-98x25x10.5; 1-100 x 33 x 9
Surface area, ft^2 total	19,350
Volume, ft^3 total	237,000
Overflow rate gpd/ft^2	640
Det. time, hr.	3.4
Type	siphon (chain)
Manufacturer	Leopold-Clari Vac

FINAL SLUDGE PUMPING

Number of Pumps	2
Max. Capacity, gpm TDH in ft	1,500 - 46
HP, each	15
Type	variable speed, centrifugal

CHLORINATION

Number of tanks	2
Dim. L'xW'xD'	71x12x75 73x30x9
Volume, ft^3 total	26,100
Det. time, min. @ peak	15

PLANT EFFLUENT METERING

Type	Sonic
Manufacturer	Endress & Hauser

PLANT EFFLUENT REUSE

Pumping

Number of pumps	2
Capacity, gpm TDH in ft.	60-80
HP, each	3
Type	Centrifugal
Manufacturer	Weinman

Filter Beds

Number of Cells	2
Dimension, dia'-ht'	4-5
Filter rate gpm/ft^2	2.4
Backwash rate gpm/ft^2	20
Backwash waste gpm	250
Media depth, ft.	2
Media size, mm.	0.5 - 0.6
Manufacturer	Sycamore

Carbon Bed

Same as filter beds except Media Size, mm	0.55 - 0.75

Storage

Number of tanks	2
Capacity, gal. each	20,000

Pumping

Number of pumps	2
Capacity, gpm TDH in ft.	200-110
Type	Centrifugal
HP, each	10
Manufacturer	Weinman

STANDBY POWER

Number of generators	2
Capacity, KVA	375
KW	300
Type	Synchronous
Manufacturer	Electric Machine Mfg.
Number of gas engines	2
Capacity, HP	618 @ 1200 rpm
Type	6-12 gas
Manufacturer	Waukesha

APPENDIX B

PROCEDURE AND EXAMPLE CALCULATION FOR THE PSEUDO-OXYGEN TRANSFER RATE

INFORMATION USED IN THE CALCULATION

The pseudo oxygen transfer rates listed in Tables 13 and 14 were calculated from information about: (a) the interstage concentration of mean soluble cBOD and mean soluble COD; (b) wastewater flow rate; and (c) the media area for an RBC shaft, which was 100,000 ft^2. Soluble cBOD and soluble COD concentrations are listed in Table 24 for the hydraulic bay experiments and in Table 25 for the organic bay experiments. Table 6 contains a listing of the actual flow rates for both the organic and hydraulic bay experiments.

EXAMPLE CALCULATION

Table 13 lists a pseudo oxygen transfer rate of 39 mg $O_2/hr/ft^2$ for the first stage of treatment (i.e. first RBC shaft) in hydraulic bay experiment number 6. This transfer rate was calculated as follows:

i) From Table 24 the mean soluble cBOD concentration entering and leaving the first stage was 46 and 30 mg/l, respectively, or a removal of 16 mg/L.

ii) From Table 6 the average flowrate for this experiment was 1,046 gpm.

iii) $$(16 \text{ mg/L})(1{,}046 \text{ gal/min})(3.785 \text{ l/gal})(60 \text{ min/hr})\left(\frac{1}{100{,}000 \text{ ft}^2}\right) =$$

$$\underline{39 \text{ mg } O_2/hr/ft^2}$$